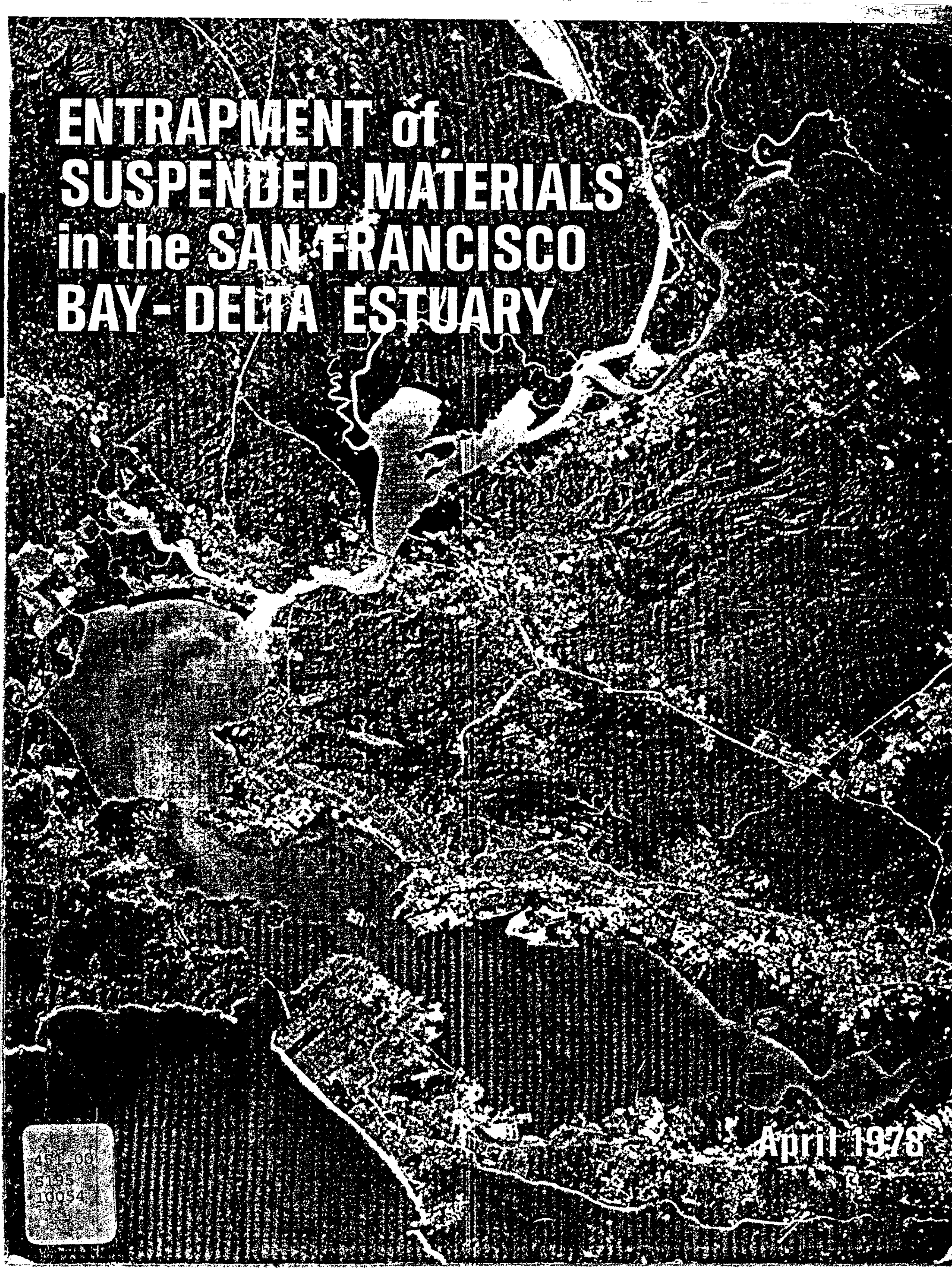
ENTRAPMENT of SUSPENDED MATERIALS in the SAN FRANCISCO BAY-DELTA ESTUARY



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ENTRAPMENT of SUSPENDED MATERIALS in the SAN FRANCISCO BAY-DELTA ESTUARY

by

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FOREWORD

This report summarizes the major findings of studies conducted by the Bureau of Reclamation (USBR) on the entrapment of suspended materials, including certain estuarine biota, in the upper San Francisco Bay-Delta Estuary during the period 1973-77. Data obtained in the studies are contained in Appendix A which is available upon request from the USBR Mid-Pacific Regional Office, 2800 Cottage Way, Sacramento, California 95825.

The USBR was assisted in the studies by the other members of the Interagency Ecological Study Program for the estuary. Within this program, the USBR and California Department of Water Resources (DWR) have undertaken the evaluation of the water quality and phytoplankton growth of the estuary; while the U.S. Fish and Wildlife Service (USFWS) and California Department of Fish and Game (DFG) have undertaken the evaluation of the zooplankton, fishery, and wildlife aspects of the program.

The information contained in this report will be used in evaluating the effects of current and proposed Central Valley Project operations on the Delta environment.

ABSTRACT

Measurements of suspended materials in the upper San Francisco Bay-Delta Estuary, California, made during the 5-year period (1968-73) preceding the present study, demonstrated that in the Sacramento River system the maximum concentration of phytoplankton, nutrients, and suspended solids occurred in Suisun Bay area. Current theory on sediment transport in estuaries, results of other studies, and data collected in the present study (1973-77) suggest two-layered flow circulation patterns in the freshwater-saltwater mixing zone combined with the flocculation, aggregation, and settling of suspended particles cause suspended materials to accumulate at concentrations exceeding those found either upstream or downstream. The general area where this accumulation occurs has been termed the entrapment zone. The present study demonstrated the entrapment zone location fluctuates tidally 2-6 miles (3-10 km) and moves landward with decreasing river discharge. The location of the entrapment zone is related to and can be approximated from salinity concentration, as measured by specific conductance. In the present study, the zone was located at the upstream end of the salinity gradient generally where the surface specific conductance was 2-10 millimho/cm (1-6 $^{o}/oo$ salinity) at Delta outflow indices ranging from 800 ft^3/s (23 m^3/s) to 64,000 ft^3/s (1,800 m^3/s). Total suspended solids (TSS), particulate nutrients, phytoplankton, *Neomysis mercedis* (Holmes), certain other zooplankton, and juvenile striped bass (young-of-the-year) are concentrated in the zone. At the highest outflows studied, the TSS concentration near the bottom in the entrapment zone exceeded 2,500 mg/l or approximately 20-40 times the upstream or downstream concentrations. At maximum tidal velocities, up to twice as much material was in suspension as at slack tide. Summer chlorophyll *a* concentrations of up to 60 ug/l were measured in the entrapment zone. These concentrations were approximately 5-20 times the upstream or downstream concentration. *Neomysis mercedis* and certain other zooplankton were concentrated at approximately 10 to 250 times the upstream or downstream concentrations while juvenile striped bass were concentrated at 200-600 times the upstream or downstream concentration depending on outflow and time of year. The lowest recorded concentrations of suspended solids and phytoplankton and lowest populations of dominant zooplankton species and juvenile striped bass occurred when the entrapment zone was located upstream of Collinsville during 1976 and 1977. These two years had the lowest Delta outflows since development of the water projects.

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CONCLUSIONS

Water quality studies conducted in the general vicinity of Suisun Bay (upper San Francisco Bay-Delta Estuary of California) during Delta outflow indices ranging from 800-64,000 ft^3/s (23 - 1,800 m^3/s) demonstrated suspended materials concentrate at the upstream end of the freshwater-saltwater mixing zone of the estuary. This area of high concentration--termed the entrapment zone--is thought to occur primarily as the result of two-layered net flow estuarine circulation. Specifically, the data obtained during the study resulted in the following conclusions:

1. Suspended solids, particulate nutrients, phytoplankton, *Neomysis mercedis* (Holmes), certain other zooplankton, and juvenile striped bass (young-of-the-year) concentrate in the entrapment zone.

2. The location of the entrapment zone is related to the magnitude and the pattern of freshwater outflow, and tidal phase. Reductions in Delta outflow result in the upstream movement of the entrapment zone.

3. The location of entrapment is related to, and can be approximated from, salinity concentration. In the present study, the entrapment zone was typically centered where the surface specific conductance was 2-10 millimho/cm (salinity of 1-6 $^o/oo$).

4. The concentration of total suspended solids and the turbidity in the entrapment and mixing zones decreased seasonally with decreased Delta outflows and suspended sediment loads. The concentrations increased with increased wind and tidal velocity.

5. Laboratory and field data indicate flocculation and aggregation of suspended materials increases above specific conductances of 1 millimho/cm (0.6 $^o/oo$). This tends to increase the settling rates of suspended particulate materials in the freshwater-saltwater mixing zone. This process is thought to significantly contribute to the quantities of materials observed in the entrapment zone.

6. The concentration of phytoplankton increased seasonally with temperature and light but was also greatly influenced by Delta outflow. Highest concentrations for any season between 1968-1977 tended to occur when the entrapment zone was located near the

upstream end of Honker Bay. The lowest summer concentrations for the 1968-1977 period were observed during the period of greatest salinity intrusion when the entrapment zone was located upstream of Collinsville.

7. The peak concentrations, as well as total population, of Neomysis mercedis and certain other zooplankton associated with the entrapment zone were also lower in 1976 and 1977 than in the higher outflow years such as 1973 and 1974. This decrease occurred as the entrapment zone moved upstream of Honker Bay into more confined channels with reduced surface area and volume.

8. There were significant lateral, as well as vertical and longitudinal, difference in the concentrations of suspended constituents throughout the study area.

RECOMMENDATIONS

Water development plans call for increased regulation of northern California water resources and increased diversion of water from the Delta. Low Delta outflows, much like occurred in 1976 and 1977, are predicted to occur more often in the future. The low production of phytoplankton, zooplankton, and juvenile striped bass (young-of-the-year) observed in 1976-77 was thought to result from the low outflow which moved the location of the entrapment zone several miles upstream of the shallow Suisun-Honker Bay area. Peak plankton production occurred when the entrapment zone was located adjacent to the shallow bays.

Results of the present study suggest the increasing frequency of low outflow may result in more frequent years of low productivity. Organisms not measured in this study may also be influenced by changes in outflow patterns. How these changes will affect the biological food web in the estuary is uncertain. For example, does low zooplankton production (which influences fish production) occur as a result of low phytoplankton production or does low production of the two occur as a result of a common factor? If zooplankton production is dependent on high phytoplankton production, then what is the optimum phytoplankton level? The following recommendations hinge upon determining the importance of phytoplankton production on the above food web.

The studies recommended below are suggested as a guide for the formulation of studies to increase the basic scientific understanding of how the entrapment zone affects estuarine biota:

1. Current water quality and biological monitoring programs in the upper San Francisco Bay-Delta Estuary should be intensified in the general area of the entrapment zone. The location of monitoring stations established throughout this area should be flexible to reflect spatial changes of the zone with outflow.

2. Additional cross sectional profiles should be conducted to determine the representativeness of sample sites especially for the biota.

3. How the lateral tidal exchange between the shallow areas of the Suisun Bay and the river channel influence the accumulation of suspended materials (including biota) in the entrapment zone under different Delta outflows should be determined.

4. The location of the entrapment zone appears to be a significient factor influencing the phytoplankton standing crop in the estuary. Several hypotheses have been presented as to how the location of the entrapment zone, relative to the Suisun-Honker Bay area, might have caused the low phytoplankton standing crop in 1976 and 1977 (p. 82). Studies should be conducted to test these hypotheses.

5. How the entrapment zone influences other ecologically important organisms not measured in the present study, sediment shoaling, and the accumulation of heavy metal and pesticides should be determined.

INTRODUCTION

The Central Valley Basin of California is drained by two major river systems - the Sacramento in the north and the San Joaquin in the south (Figure 1). These river systems converge in the Sacramento-San Joaquin Delta (termed Delta) which encompasses 737,000 acres interlaced with 700 miles of meandering waterways. Water flows from the Delta into Suisun, San Pablo, and San Francisco Bays prior to entering the Pacific Ocean at the Golden Gate (Figure 2).

The Delta and Bays, commonly called the San Francisco Bay-Delta Estuary, is subject to saltwater intrusion and tidal action. In recent years, the freshwater flow through the estuary has been increasingly regulated by the operations of the Federal and State water projects.

The physical features of the estuary, including descriptions of the agriculture, industries, cities, transportation, waste discharges, recreation, and present and proposed water resources development facilities, have been described in detail in a number of reports (Kaiser Engineers, 1969; USBR, 1972; Calif. DWR, 1974; Calif. SWRCB, 1975).

In 1968, the USBR initiated environmental studies of the upper San Francisco Bay-Delta Estuary to delineate existing or potential problems associated with the operation of the Bureau's Central Valley Project (CVP). These studies included an evaluation in 1973 of surface water quality data collected in the Bureau's routine water quality program from 1968 to 1973. The purpose was to determine which factor(s) controlled phytoplankton growth in the upper estuary.

The long-term average concentration of phytoplankton was found to be considerably higher in Suisun Bay than in the adjacent upstream or downstream areas even though water transparencies were lowest in Suisun Bay. A number of algal growth potential (AGP) tests were conducted and it was concluded some factor(s) other than light, temperature, salinity, or nutrients were responsible for the relative high phytoplankton standing crop observed in Suisun Bay (Arthur, 1975).

Further examination of other water quality constituents collected throughout this area from 1968-73 demonstrated the concentration of suspended materials, including certain zooplankton, generally peaked in Suisun Bay.

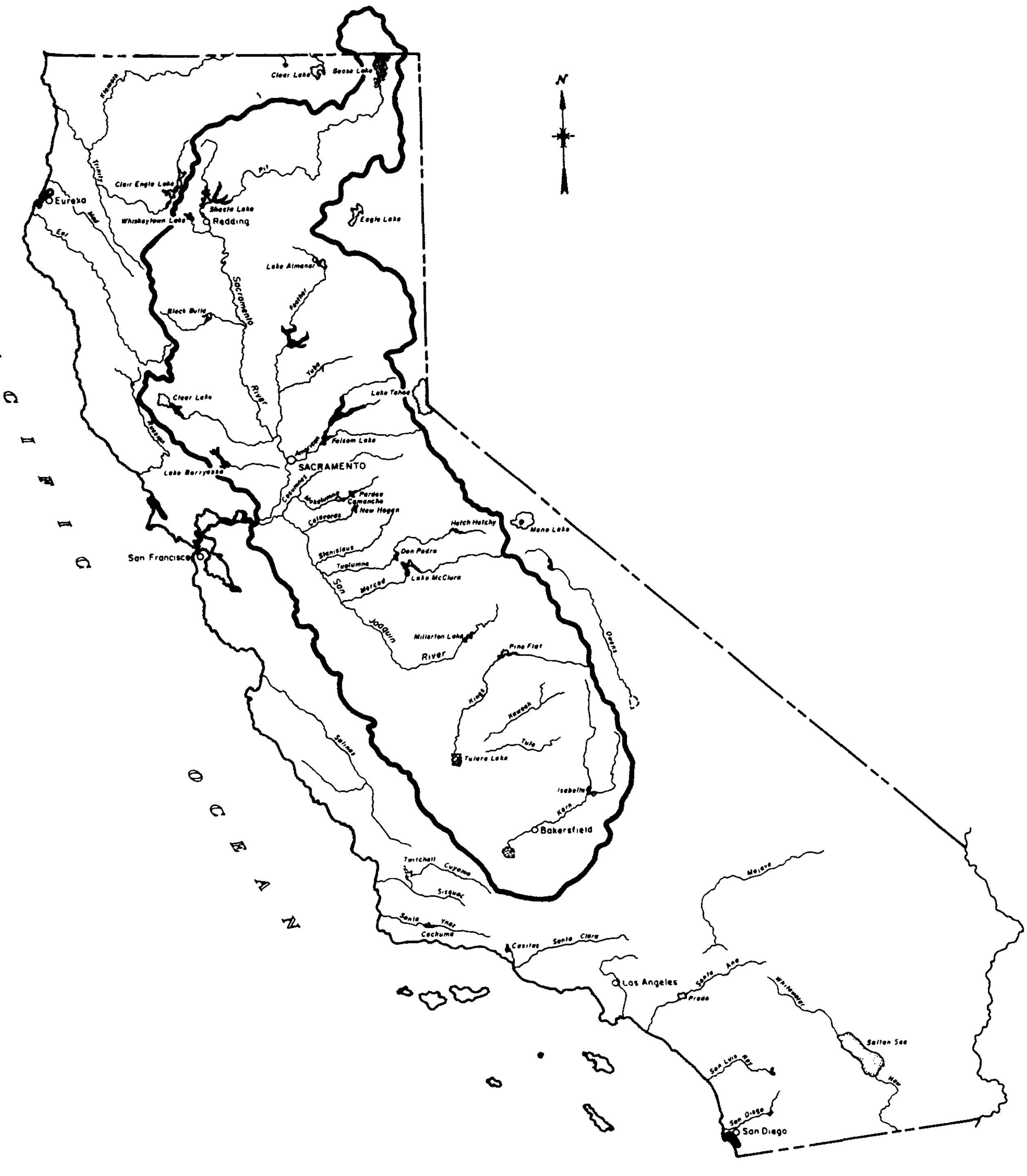

Figure 1. Sacramento-San Joaquin River drainage basin.

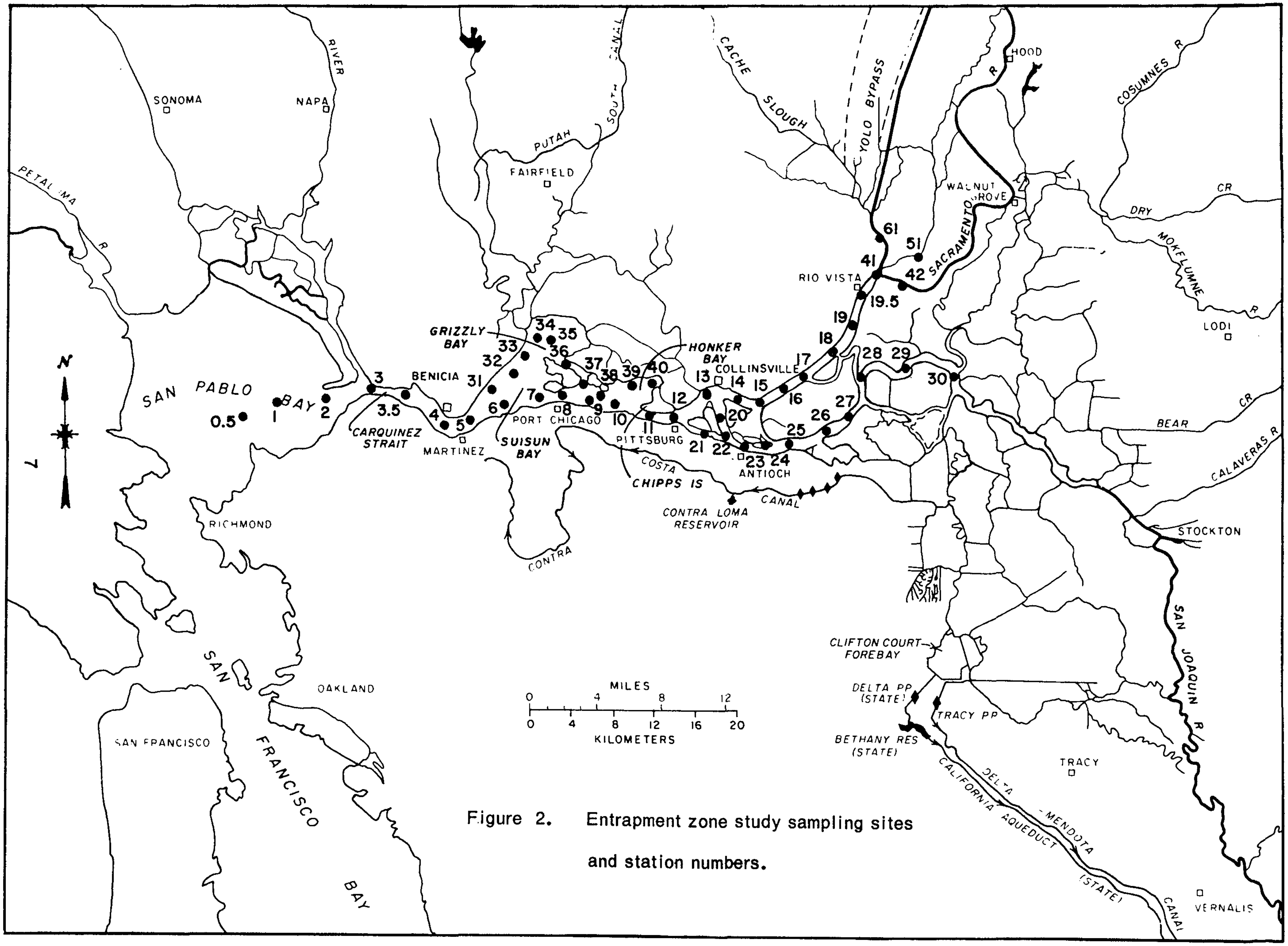

Figure 2. Entrapment zone study sampling sites and station numbers.

Introduction

Studies in other estuaries have demonstrated a turbidity maxima occurs in the area where fresh and saltwater mix as a result of two-layered circulation (Nichols and Poor, 1967). Consequently, a field study was conducted to determine the relationship between suspended materials and salinity concentration in the upper San Francisco Bay-Delta Estuary. These data demonstrated suspended materials were concentrated longitudinally and vertically throughout the upper estuary in the general area where fresh- and saltwater initially mix. The hypothesis was advanced (Arthur, 1975) that suspended materials tend to concentrate in waters with specific conductances in the 2-10 millimho/cm (1-6 $^{o}/oo$) range as a result of two-layered flow. Laboratory flocculation studies demonstrated that seawater brine added to Sacramento River water increased the aggregation and settling rates of suspended materials, suggesting these factors increase the concentration of suspended materials found in the area of maximum accumulation. The term entrapment zone was used to describe this area. Terms used by others to describe this general area of maximum accumulation of suspended materials are the turbidity maxima, critical zone, nutrient trap, sediment trap, and null zone.

OBJECTIVES OF STUDY

The present study was designed to gain an understanding of the entrapment zone and to attempt to answer questions brought out in the preliminary investigation. Specifically, the primary objectives of the study were to:

1. Verify the presence of an entrapment zone in the upper San Francisco Bay-Delta Estuary.
2. Characterize the distribution of suspended materials in the entrapment zone.
3. Predict the change in location of the entrapment zone with changing Delta outflows.
4. Determine if the entrapment zone influences the water quality and the abundance of estuarine biota.

METHODS

The primary variable in the entrapment zone studies was Delta outflow. Sampling runs were conducted during 11 periods over a range of Delta outflows, between September 1973 and September 1977, Table 1. The vertical distributions of suspended materials, including certain estuarine biota, were determined at a number of sites in the upper San Francisco Bay-Delta Estuary. In 1973-74 sites were sampled on the Sacramento River between Collinsville and Pinole Point in San Pablo Bay. Additional stations were established in the 1976-77 sampling runs upstream of Rio Vista on the Sacramento River and on the San Joaquin River, Figure 2. In addition to the special runs, routine water quality monitoring data were also evaluated for the period 1973-77.

Table 1. Delta outflow index at time of sample runs.

Run No.	Dates	Delta outflow index* (ft^3/s)	(m^3/s)
1	Sept. 26 & 27, 1973	13,000	(370)
2	March 21, 1974	64,000	(1,800)
3	May 30 & 31, 1974	20,000	(570)
4	Aug. 19-21, 1974	13,000	(370)
5	July 8 & 9, 1976	5,200	(150)
6	Aug. 5 & 6, 1976	3,700	(100)
7	Aug. 18 & 19, 1976	3,600	(100)
8	Dec. 8, 1976	5,000	(140)
9	April 27 & 28, 1977	4,000	(110)
10	July 12-14, 1977	2,500	(71)
11	Aug. 23 & 24, 1977	800	(23)

* Calculated average during each run (USBR data, see page 26).

Sample Collection

Sample collection procedures changed slightly during the course of the study as improvements were made in the equipment. Water quality and phytoplankton samples were collected by the USBR while the DFG collected the zooplankton, *Neomysis*, and striped bass samples, Table 2.

Methods

Samples were collected primarily at channel sites (Figure 2) at various tidal stages; however, to collect the extensive number of samples required on each run, it was necessary at times to start approximately 1 hour prior to the calculated tide time and end about 1 hour late at the last site. Cross section profiles were also conducted at a number of sites during the study. Data collected in the study are included in Appendix A, available from the USBR.

Table 2. Constituents measured during the entrapment zone study.

Constituent*	Data source	
	USBR	DFG
EC	x	
Nutrients - N&P	x	
Turbidity	x	
Suspended solids	x	
Chlorophyll	x	
Pheo-pigments	x	
Phytoplankton	x	
Dissolved silica	x	
DO	x	
Neomysis mercedis		x
Zooplankton		x
Striped bass		x

* All water quality constituents were collected at varying depth intervals between 3 feet below the surface to 3 feet off the bottom (maximum depth interval was seldom over 10 feet). Not all parameters were collected on every sampling run.

The water quality samples were collected by lowering a weighted hose to the desired depth and then pumping the sample on board using a self-priming marine utility pump. The samples were generally collected at the 3-foot depth (1-meter), as in the routine USBR-DWR monitoring programs, and at 5- or 10-foot (1.5- or 3-m) intervals but the intervals varied with the parameter and the run. Adequate time was allowed between samples to flush the hose. A rod was attached to the intake to keep the hose rigid and more accurately maintain collection of the bottom samples at approximately 3 feet (1 m) off the bottom. The hose was marked to determine sample depths. Site depth was determined with a fathometer.

Methods

Neomysis and other zooplankton samples were collected by the DFG using a diagonal tow method (USBR, 1977). A different size net was used for Neomysis than for zooplankton. The nets were lowered to the bottom and towed at constant speed while gradually being raised to the surface. The tow time was about 10 minutes and covered about 0.5 mile (0.9 km) distance. The nets had meters attached to determine the volume of water filtered.

Juvenile striped bass (young-of-the-year) data were obtained from the routine DFG Striped Bass Monitoring Program.

Neither velocity nor direction of flow measurements were made during this study. Tidal stage times for the various sites were calculated from Golden Gate Bridge (mouth of the estuary) tide estimates using the U.S. Department of Commerce NOAA tidal tables.

Sample Analysis

Surface temperatures were measured at the time of collection using either a glass-mercury thermometer or a Yellow Springs thermistor. Samples for turbidity and specific conductance were either measured in the field at the time of collection or at the end of the day's run. A Hach 2100A turbidimeter, calibrated with formazine standards, was used for measurements of turbidity. Specific conductance (EC), corrected for 25C, was used as a measurement of salinity. Analyses for specific conductance were made on the first run with a Beckman RB-3 solu-bridge with manual temperature compensation; on the second run a Beckman R3341 with automatic temperature compensation was used; and on the subsequent runs Beckman RC-19 manual temperature-compensated digital meters were utilized.

The following samples were preserved in the field and analyzed in either the USBR or DFG laboratories using the indicated methods:

1. Ammonia - Vacuum filtration was used. Filtrate was frozen. Analysis was with the low level ammonia method (Technicon AAII Methodology, Industrial Method 154-70W).

2. Nitrate plus nitrite - Vacuum filtration was used. Filtrate was frozen. Analysis was with the cadmium reduction method (Technicon AAII Methodology, Industrial Method 100-70W).

3. Organic nitrogen - The whole sample was frozen. The samples were digested with purified potassium persulfate and sulfuric acid (USEPA, 1971), then neutralized with NaOH using phenolphthalein as an indicator and analyzed using the automated ammonia method (Technicon Auto Analyzer II Methodology, Industrial Method 98-70W).

4. Orthophosphate - Vacuum filtration was used. Filtrate was frozen. The phosphate (ortho) method (Technicon Auto Analyzer Methodology, Industrial Method AAII 94-70W) was used.

5. Total phosphorus - The whole sample was frozen. The phosphate (ortho) method (Technicon Auto Analyzer Methodology, Industrial Method AAII 94-70W) was used after first digesting the samples with potassium persulfate and sulfuric acid (USEPA, 1971).

6. Dissolved silica - Vacuum filtration was used. The filtrate was then analyzed using the silica automated method (Technicon AAII Methodology, Industrial Method 105-71W).

7. Suspended and volatile solids - Whole samples were iced in the field. The suspended materials were collected by vacuum filtration on 0.45-micron pore size silver filters, dried at 105 C and combusted at 550 C, and weighed on an analytical balance.

8. Chlorophyll _a_, pheo-pigments, and percent chlorophyll _a_ - Samples were vacuum filtered and collected on glass fiber filter discs pretreated with a $MgCO_3$ suspension, then immediately frozen. Analysis followed the spectrophotometric method for chlorophyll _a_ and pheo-pigments (Strickland and Parsons, 1968), with a slight modification by Ball (1977). In 1976 and 1977 the fluorometric method for chlorophyll _a_ and pheo-pigments (Strickland and Parsons, 1968) was used.

9. Phytoplankton identification and enumeration - Samples were preserved with Lugols solution. They were placed in 3.18 mm deep special settling chambers, allowed to settle, and enumerated at the genus level using a Unitron inverted microscope.

10. Neomysis and zooplankton samples were preserved in a Formalin-rose bengal solution. They were subdivided and identified to species level at the DFG laboratory in Stockton, California.

Data Evaluation

For evaluation, the multidepth data for the various parameters were usually arranged by depth and station on a figure with vertical-longitudinal sections of the Sacramento and San Joaquin Rivers. No attempt was made to determine exact channel depths due to the variability across the channel. Lines were constructed to illustrate contours of equal concentration (isocontours) with depth and geographical location (eg. Figure 7). In most cases, the 3-foot depth 2-10 millimho/cm specific conductivity (referred to as SUR EC in this report) ranges were included with isocontours of other parameters to illustrate their relationship (eg. Figure 13). Concentration ranges between the isocontours were then shaded (eg. Figure 13).

LITERATURE REVIEW

To inform those unfamiliar with estuarine processes, this section includes a brief discussion of estuarine classification, based on circulation, and summarizes the hydraulic, physical, and chemical processes which have been observed to influence the entrapment of suspended materials and biota in this and other estuaries.

Estuarine Circulation and Entrapment

Several factors are thought to influence the formation and degree of suspended materials entrapment in estuaries. These factors include the type of estuarine circulation; the type of suspended materials present; and the flocculation, aggregation, and settling rates of suspended materials.

Pritchard (1967) defines an estuary "as a semi-enclosed coastal body of water which has a free connection with the open sea and within which seawater is measurably diluted with freshwater derived from land drainage." Accordingly, the primary criterion used in the classification of estuaries is the type of circulation patterns formed when the inflowing freshwater meets the seawater. One system of classification presented by Bowden (1967) includes four basic types: salt wedge; two-layered flow with entrainment, including fjords; two-layered flow with vertical mixing; and vertically homogenous estuaries.

Bowden's classification system is arbitrary with few estuaries meeting a specific classification criteria 100 percent of the time since estuarine circulation varies with riverflow, wind, topography, tidal action, and temperature. Based on Bowden's classification system, estuaries vary from the highly stratified, riverflow-dominated, salt wedge estuary to the well mixed, vertically homogenous, tidal-flow dominated estuary. Circulation in most estuaries ranges somewhere between these two extreme patterns, and, in many cases, different circulation patterns can occur within a single estuary.

A typical feature of estuaries is the landward intrusion of denser seawater under seaward flowing less dense freshwater. (Bowden, 1967). The net landward flow near the bottom is persistent and results in an area where the landward and seaward density currents have an equal and opposite effect (Simmons, 1955; Schultz and Simmons, 1957; and Hansen and Rattray, 1966). The general area where this phenomenon occurs in an estuary has been termed the null zone (Hansen, 1965) or the area of no-net motion (Nichols and Poor, 1967; and Pritchard, 1967). The nullification of net bottom flows in this area allows the heavier and more dense suspended materials to accumulate. This area of accumulation has been termed the entrapment zone (Arthur, 1975), the critical area (Massmann, 1971), the turbidity maxima (Postma, 1967), the nutrient trap (anonymous), and the sediment trap (Schubel, 1968).

According to Bowden, estuaries having circulation characterized by two-layered flow with vertical mixing are generally shallow. The tidal currents in this type of estuary extend throughout the depth mixing the fresher water downwards and the more saline water upwards. The area where this occurs is termed the mixing zone. Although vertical mixing does occur there still are two opposing layers of net flow with a plane of no-net motion between. Generally this plane is above mid-depth. A distinct interface does not occur between the two layers as in the more stratified type of estuaries such as the salt wedge type; however, salinity continuously increases from the surface to the bottom with the maximum gradient occurring at the plane of no-net motion. A wide range in the degree of stratification exists in this type of estuary. This range in stratification is dependent on the ratio of the amplitude of tidal currents to the riverflow and depth. The increase in salinity from surface to bottom may vary from 1-10 $^{o}/oo$ (specific conductance of approximately 1.5-15 millimho/cm). The net discharge from the upper layer in this type estuary may be several times the river inflow. For example, the net seaward transport in the upper layer may be 20 times the riverflow while the net landward transport may be 19 times the riverflow. Estuaries of the Chesapeake Bay system are of this type and their hydraulics have been described quite extensively by Pritchard (1956) among others.

The upper San Francisco Bay-Delta Estuary seems most often to fall into the two-layered flow with vertical mixing classification. Other portions of the Bay fall into different circulation classification depending on river inflow and time of year.

Another factor suggested as contributing to the accumulation of suspended materials in the entrapment zone is the flocculation (the aggregation of small waterborne particles) and settling of riverborne materials which enter and circulate within estuaries.

According to Krone (1972), for years salt flocculation has been postulated to contribute to the observed deposition of riverborne suspended sediments where river water mixes with seawater. Postma

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(1967) also states that for many years flocculation has been suggested as contributing to the turbidity maximum and cites Luneburg (1939) as one of the earlier proponents of this hypothesis.

Simmons (1955), Schultz and Simmons (1957), Humby and Dunn (1975), and Krone (1972), among others state that the saltwater density current (which causes two-layered flow circulation pattern) is a major factor influencing sediment transport and shoaling in estuaries. Nichols and Poor (1967) in their studies of the Rappahannock Estuary (which has salinity stratification similar to the San Franisco Bay-Delta Estuary) also dealt with the matter of sediment transport and formation of a turbidity maximum (entrapment) as related to estuarine circulation. They described in detail two-layered flow with vertical mixing circulation patterns for the estuary. They found colloidal and fine-grained sediments remaining in suspension for long periods will be transported, on the average, either upstream or downstream depending on the time the material is suspended in either the seaward- or landward-flowing layer.

Nichols' and Poor's studies also demonstrated the level of no-net motion can extend from the channel into the adjacent shoal areas and it slopes upward from the left to the right side reflecting the effect of the earth's rotation (Coriolis force). Consequently, net upstream flow on the right side takes place at all depths over the greater part of the shoals. When waters are even moderately stratified due to salinity differences, the level may reach far shoreward near the bottom; however, when waters are mixed, i.e., tide or wind, the level may intersect the bottom near the channel shoulder. From this type of information, they concluded the level of no-net motion is not a plane sloping gently upward from the head to the mouth but is an undulating surface varying both longitudinally and laterally throughout the estuary.

According to Simmons (1955) and Schultz and Simmons (1957), the most significant effect of density currents on sediment transport in estuaries is to cause the bottom flood currents to predominate over the bottom ebb currents by increasing the velocity and duration of the former and decreasing the velocity and duration of the latter. This creates an effective trap for sediments on and near the bottom, preventing their movement to the sea and causes the bottom to be shoaled and unstable. A feature observed by Nichols and Poor (1967) in the Rappahannock Estuary which also contributes to the upstream movements of sediments in the lower layer is low velocity occurs for a longer time near high slack water than during low slack water allowing a greater period of time for settling at the upstream position of tidal excursion.

Nichols' and Poor's studies further demonstrated that within the area of no-net motion (null zone) suspended solids concentrations were higher than the source river water with concentrations typically increasing toward the bottom. Upstream-flowing water (near the bottom) was more sediment enriched than the overlying layers resulting in the highest concentrations occurring just above the estuary floor. They found that although the net transport was upstream in the channel, it was downstream over the greater part of the shoals.

Nichols and Poor also concluded that as riverborne material was carried into the basin (large bay), a large portion settled, because of decreased velocity, from the upper layer to the lower layer where it then could be transported upstream.

Suspended sediment size analyses in their studies showed much of the material transported through the estuary consisted of silts and clay particles less than 62 microns in diameter. The longitudinal distribution of the coarse fraction (less than 3 percent of the total) is similar to the distribution for total sediments with concentrations increasing upstream and from the surface to the bottom.

Nichols and Poor also found pronounced variations in the type of suspended material found throughout the estuary. Low-density materials, such as organic detritus and plankton, formed higher percentages in the near-surface water while more dense materials were found near the bottom. They determined this density differentiation results in selective net transport of more dense materials upstream and less dense materials downstream. They further concluded that the less dense material was the primary material being deposited over the shoals.

Postma (1967) describes the turbidity maxima normally seen in estuaries as being attributed to the estuarine circulation patterns previously described. In this regard, he also states it is theoretically possible for suspended particles being transported in the process to be circulated repeatedly through the estuary before finally being deposited or escaping from the system. Additionally, the particles entrapped in the cycle can be of either freshwater or marine origin.

Other factors listed by Postma (1967) as being important to the formation of turbidity maxima are the amount of suspended materials in the river or sea (bay), the strength of the estuarine circulation, and the settling velocities of the materials being transported. Postma goes on to state the process causing the turbidity maxima can occur in a well mixed estuary as well as in highly stratified estuaries. Furthermore, larger riverflows push the turbidity maxima toward the sea while, conversely, lower river discharges limit the development of the zone (since estuarine circulation becomes minimal).

Schubel (1968) and Schubel and Carter (1975) have also reported zones of turbidity maxima in Chesapeake Bay. They found throughout the year the seaward boundary of the turbidity maximum was marked by a steep longitudinal gradient in the concentration of suspended sediment.

Schubel and Carter (1975), like Postma, also reported a downstream movement of the turbidity maximum during periods of high runoff. They were able to correlate the turbidity maximum with the sediment concentration in the Susquehanna River during the spring runoff. During other periods, they attributed the sediment trap to the continual resuspension of bottom sediments produced by the net nontidal estuarine circulation which entraps much of the sediment within the estuary. They also found maximum concentrations of suspended matter occurred near the point of maximum ebb and flood velocities with minimum concentrations occurring shortly after slack water.

Similar patterns of suspended sediment distribution as described above have been reported for other estuaries. These include the Gironde Estuary in France (Allen, et al., 1976), the Amazon River in Brazil (Gibbs, 1976), and the Savannah Estuary in the U.S. (Meade, 1972), among others.

Studies in the San Francisco Bay-Delta Estuary

As early as 1931, Grimm stated there were net upstream bottom currents in the San Francisco Bay Estuary. Since then, studies by the U.S. Army Corps of Engineers (USCE, 1967) and the U.S. Geological Survey (USGS - McCulloch, et al., 1970; Conomos, 1975; Conomos, et al., 1970, 1971, and 1974; Peterson et al., 1975a; and Smith, 1966) have demonstrated a two-layered flow circulation pattern exists throughout much of the Bay system. This was determined from observations of salinity distribution, studies of the distribution pattern of seabed drifters released at various points throughout the Bay-Delta system and adjacent Pacific Ocean, and from harmonic analysis of flow data collected by the USCE. The USGS studies indicated there are net bottom flow movements from the Pacific Ocean and from the northern edge of South Bay (approximate location of the Oakland Bay Bridge) into San Pablo and Suisun Bays. They also concluded

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fluids or solids entrained by the currents would follow a similar distribution pattern. Fischer (1976), in his discussion on mixing and dispersion in estuaries describes two-layered flow as being caused by gravitational circulation. He states that in an estuary with very irregular topography, such as the San Francisco Bay-Delta Estuary, salinity intrusion is greatly increased by "trapping" and "pumping" (two forms of tidal dispersion) and wind dispersion.

Recent studies by the USCE (1977) demonstrated that dredged spoils which were tagged with irridium (a tracer which can be analyzed by neutron activation) and released in the southeastern portion of San Pablo Bay were recovered in Suisun Bay (suggesting upstream sediment transport from San Pablo Bay into Suisun Bay).

Peterson, et al., (1975a) described the location of the nontidal current null zone (the area of maximum suspended materials) in the northern San Francisco Bay, the effects of riverflow on the location of this zone, and seasonal changes in the accumulation of suspended materials.

Hydroscience, Inc., consultants to the Interagency Ecological Study Program California (Calif. DFG, et al., 1975-76), have recently developed a mathematical model capable of reproducing salinity and suspended solids distribution from data obtained in the current studies. In their report (O'Connor and Lung, 1977), they review the previous work on estuarine circulation leading up to the development of their two-dimensional (vertical) hydrodynamic, salinity transport, and suspended solids distribution model for the upper San Francisco Bay-Delta Estuary.

Entrapment of Estuarine Biota

Although there is currently a fairly good understanding of how two-layered flow influences sediment transport in estuaries, few studies describe the effects of two-layered flow on the estuarine biota.

Gibbs (1976) studies on the Amazon River demonstrated the formation of a turbidity maximum including phytoplankton oceanward of the mouth and paralleling the coast as a result of two-layered flow with entrainment and mixing.

Cronin and Mansueti in "Proceeding of a Symposium on the Biological Significance of Estuaries" (1971) state that many of the coastal plain estuaries have a two-layered flow pattern which is of unique importance to the biota that live there. Among other things, two-layered circulation patterns results in transport of organisms

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in the surface water toward the sea and those in the bottom waters to the river.

According to Cronin and Mansueti, zooplankters often have a diel vertical migration cycle which in a two-layered flow system translates into upstream movement during the day and a downstream movement at night. This results in a circular motion which retains the species near its optimal salinity range. They also indicated that the eggs and larvae of some freshwater spawning fish are transported downstream while those of some saltwater spawning fish are transported upstream by the two-layered flow circulation pattern to the plankton-rich, low salinity nursery area (termed the entrapment zone in this report).

Cronin and Mansueti believe the blue crab distribution is also influenced by the net two-layered flow pattern. The megalops, or second stage larva, settle to the bottom layers after being spawned in the ocean. They are transported upstream in the bottom flows where they are widely dispersed. Mating of the adults occurs in waters of low and middle salinities and the female is rapidly transported back downstream - perhaps gaining some advantage from the net downstream drift of the surface water.

In the same symposium, Massmann (1971) also pointed out inflowing bottom waters transport fish larvae and other plankton upstream to the area where the currents recycle and trap nutrients, sediments, detritus, and planktonic organisms.

The DFG has been actively engaged in studying the San Francisco Bay-Delta Estuary for a number of years and has produced numerous publications on the estuarine fishery and zooplankton. As early as the 1960's the DFG concluded that of the environmental factors studied, chlorinity was most responsible for species distribution of zooplankton, and zoobenthos (Kelley, 1966). Outflow and salinity were thought to be the dominant factors controlling longitudinal distribution of a number of species of fish in the estuary (Turner and Kelley, 1966). Turner and Chadwick (1972) indicate the maximum concentration of juvenile striped bass (young-of-the-year) occur within specific salinity ranges. Heubach (1969) indicated Neomysis mercedis was most abundant in the estuary from freshwater to 4 ^{o}/oo chlorides and least abundant at salinities exceeding 10 ^{o}/oo chlorides.

As previously discussed, the USGS has actively been engaged in studies of the San Francisco Bay-Delta Estuary for a number of years. Their studies have included evaluations of the factors influencing phytoplankton distribution in the northern San Francisco

Bay (Conomos and Peterson, 1974; Peterson, et al., 1975a; Scrivani, 1975). In summary, they found the summer phytoplankton maximum occurs in the "null zone", and their spatial distribution varies daily with tides and annually with changes in river inflow.

Siegfried, et al., (1978) conducted ecological studies in the area from Chipps to Decker Island in the San Francisco Bay-Delta Estuary during 1976. A portion of their studies was conducted in coordination with the present (USBR) studies. Discrete vertical measurements were taken monthly for physicochemical parameters (temperature, salinity, pH, and dissolved oxygen), benthos, phyto- and zooplankton, benthic-pelagic shrimp, bottom sediment type, and sediment heavy metal concentration at each site.

Among other things, Siegfried, et al., indicated the substrate in the entrapment zone consisted of silts and clays (as compared to sand downstream) which shifted upstream with the entrapment zone as riverflows decreased during the summer of 1976. According to them a silt-clay type of substratum is among the most important factors determining benthic species composition and standing crop in the estuary. They found, in general, the changes in the benthic community composition were related to changes in salinity and sediment composition which was associated with the entrapment zone. Analysis of the bottom sediments indicated the highest concentrations of heavy metals were found in the silt-clay sediments; presumably the result of absorption by flocculated materials in the zone. However, no mention was made of the possible significance of the higher heavy metal concentrations to the biota.

Siegfried, et al., also found plankton and pelagic shrimp distributions were related to salinity. Their studies have demonstrated the size distribution of *Neomysis* varies with location within the entrapment zone. Large mysids were centered at the upstream end of the zone, whereas, small mysids were centered downstream. The differences in distribution were attributed to interaction between two-layered flow and differential vertical distribution of mysids of various sizes.

Measurements since 1968 of suspended materials, including certain estuarine biota, by the USBR and the other members of the Interagency Ecological Study Program have demonstrated that the maximum concentration of phytoplankton, *Neomysis mercedis*, certain other zooplankton, and juvenile striped bass (young-of-the-year) occur in the entrapment zone (Arthur, 1975; Macy, 1976; and Calif. DFG, et al., 1975, 1976). Undoubtedly, other estuarine biota are directly or indirectly influenced by two-layered flow estuarine circulation.

CONCEPTUAL MODEL

The following discussion conceptually describes how certain types of suspended materials may become entrapped or accumulate in the upper San Francisco Bay-Delta Estuary. The generalized discussion is based on: general theory and results of other studies, as presented in the literature review, and data collected in the present study.

The primary driving force causing the net upstream flow in the lower layer of water results from the greater density of seawater than that of freshwater (Figure 3). Because this density difference exists, freshwater entering the estuary with a greater hydraulic head tends to flow over the denser, more saline water. The force of the freshwater varies with riverflow. The greater the riverflow, the greater the hydraulic head and consequently, the greater the seaward driving force. High riverflows drive the mixing zone farther seaward, increase the salinity stratification, and compress the mixing zone.

Forces tending to disrupt vertical salinity stratifications are the turbulent forces which increase with increasing tidal velocity and the turbulent forces created by increasing wind velocity. Vertical stratification is less intense during periods of high winds and high tidal velocities.

The San Francisco Bay-Delta Estuary is characterized as having two-layered flow with vertical mixing (Figure 4) as a result of the landward density force and hydraulic force of the river. When tidal flows are averaged, the net flow in the upper layer is seaward while it is landward in the lower layer. This creates an assumed plane of no-net motion between the layers. In many estuaries it is above mid-depth in the channel. Tidal currents supply the energy for the vertical mixing of the landward flowing more saline water with the overlying seaward flowing fresher water. There is an assumed net vertical flow upwards into the seaward flowing layer. This upward vertical flow theoretically increases the surface outflow from the estuary over the amount of freshwater inflow. There is also a theoretical zone in the upstream portion of the estuary where the landward force in the lower layer of water is equaled by the seaward force. As a result, the forces are nullified resulting in an area of no-net flow or null zone in the lower layer of water.

The two-layered flow pattern influences the maximum tidal velocities of each layer. The net downstream flow in the surface

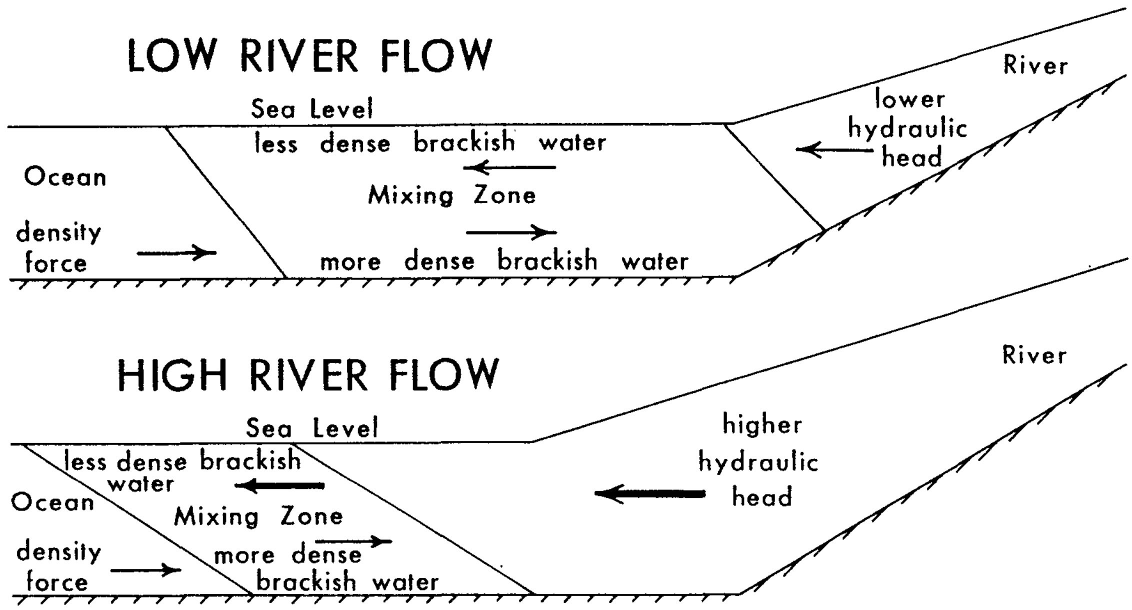

Figure 3. Conceptual schematic of the primary driving forces responsible for two-layered flow circulation in the estuary. The higher hydraulic head in the river during high outflows moves the mixing zone of fresh and salt water seaward and increases the vertical salinity stratification.

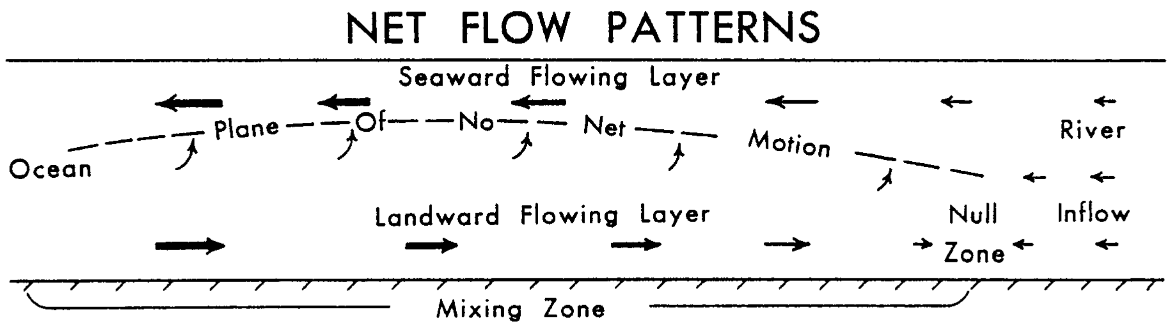

Figure 4. Conceptual schematic of net flow patterns in a two-layered flow with vertical mixing estuary.

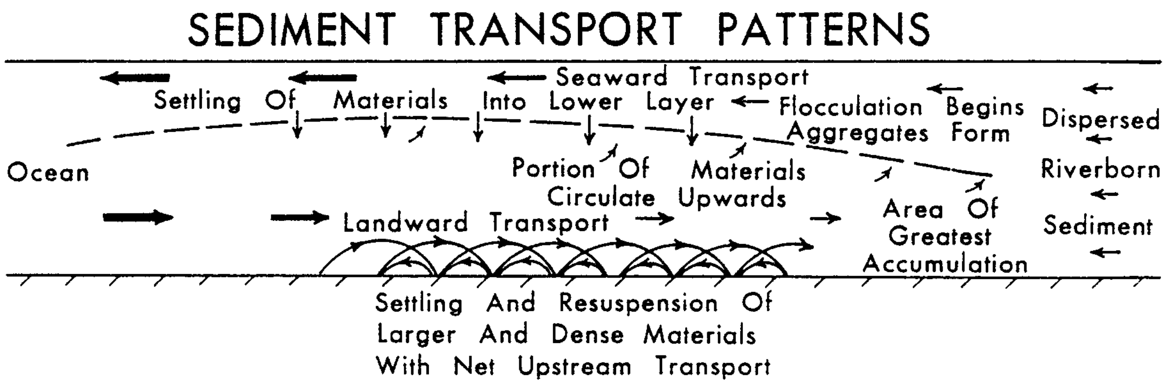

Figure 5. Conceptual schematic of transport patterns of suspended materials in a two-layered flow with vertical mixing estuary.

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layer increases surface tidal velocities during ebb tides and decreases surface velocities during flood tides. In the lower layer, the reverse occurs. The net upstream flow increases velocities in the lower layer during flood tides and decreases velocities during ebb tides. This increases the net upstream transport of materials along the bottom.

Several factors influence the transport of suspended materials (Figure 5). As freshwater enters the estuary, it mixes with the more saline water. The increased salinity starting at about 1 millimhos/cm specific conductance (0.6 $^{o}/oo$), as found in our laboratory experiments, enhances flocculation of the suspended inorganic particles (primarily in the 2-10 micron size range). The aggregates that form settle at rates greater than the unaggregated materials. The particles and aggregates are transported downstream until they either settle through the plane of no-net motion into the lower layer or are transported out of the estuary. The net movement of sediment in the lower layer is upstream. Larger and denser materials may settle out near slack tides and then be resuspended as tidal velocity increases. The less dense and smallest suspended materials tend to be carried into the upper layer as a result of the net upward vertical flow and are transported seaward. A portion of the suspended material is transported laterally into shallow areas and may be deposited in shoals. Materials resuspended by tidal or wind action in the shallow areas may also be transported back to the channel. Suspended materials in the lower layer may be transported upstream to the entrapment zone where the area of maximum concentration and maximum residence time occur. Theoretically, the entrapment zone occurs where the net vertical velocities are the greatest. This area is thought to be slightly downstream of the null zone. As the aggregates move into the fresher water, partial deaggregation may occur. The materials that enter the upper layer are again transported seaward and, theoretically, can be recirculated several times. Under low riverflows, the majority of the suspended sediment settles into the lower layer farther upstream in the estuary than during high flows. During high riverflows, a larger portion of the fine suspended sediment is transported to the ocean than during low flows.

RESULTS AND DISCUSSION

The results of the suspended materials entrapment study, conducted in the upper San Francisco Bay-Delta Estuary from September 1973 through September 1977, are typical of an estuary characterized by two-layered flow with vertical mixing.

Estuarine Circulation

The formation of the entrapment zone is the result of dynamic physical and chemical forces within the estuary in the area where freshwater and saltwater mix. The primary factor responsible for entrapment of suspended materials is the net two-layered flow estuarine circulation pattern.

RIVERFLOW

River inflow is the primary force regulating the variation in hydraulic circulation patterns of any given estuary. As a result, this study was designed to characterize the suspended material entrapment under as many variations in river inflow as possible. The Delta outflow index (net flow past Chipps Island, site 11) is used as the measure of river inflow to the estuary throughout the report. As there are often misconceptions as to what the index represents, some discussion is warranted.

The Delta outflow index (Table 1) is calculated daily by the USBR for project operations. It consists of the Sacramento River discharge at Sacramento and the San Joaquin River discharge at Vernalis less the Delta export and the estimated Delta consumptive use. An estimated Delta consumptive use table is used by both the USBR and the DWR. Consumptive use values vary from 4,600 ft^3/s (130 m^3/s) in August to minus 1,000 ft^3/s (-30 m^3/s) in January. The same table is used from year to year, however, crop usage patterns and weather patterns do change. As a result, the outflow could be off plus or minus 0-2,000 ft^3/s (0-60 m^3/s) or more especially during the late summer months because of an over or under estimate in the consumptive use. The Yolo Bypass and other peripheral streams also contribute significant discharges to the Delta outflow during periods of high runoff (especially over 50,000 ft^3/s or 1,400 m^3/s). Measurements of these additional discharges are not available daily and are generally insignificant during the period of low Delta outflow. They are, therefore, not required or included in the Delta outflow index which is used for operation of the project.

Another outflow measurement, the monthly historical Delta outflow, includes the measurements of all significant discharges but still uses the estimated consumptive value. The historical Delta ouflow was calculated to evaluate winter discharges from the Delta and is compared to the Delta outflow index in Figure 6. Since the Delta outflow index is the number most readily available, it has been used in this report to indicate Delta outflow unless otherwise stated. However, although the Delta outflow index is the best number readily available it is only an approximation of the actual Delta outflow at any given time.

The 1973-1975 water years were above normal, while 1977 was the driest year, and 1976 and 1977 were the driest two consecutive years on record. No sampling runs were conducted in 1975.

The sampling runs in 1973 and 1974 were conducted at Delta outflow indices of 13,000-64,000 ft^3/s (370-1,800 m^3/s), while in 1976 and 1977 they were at 800 – 5,000 ft^3/s (23-140 m^3/s).

SALINITY INTRUSION

Salinity intrusion is primarily regulated by the amount of riverflow to the estuary. This is demonstrated in Figure 7, where salinity profiles ranging from periods of very little intrusion, following the 1974 floods, to periods of very high intrusion, during the 1977 drought, are characterized. The 2-25 millimho/cm specific conductance (EC) (1-15 $^{o}/oo$ salinity) range has been arbitrarily shaded to facilitate comparisons of salinity intrusion at different outflows.

In addition to the quantity of Delta outflow, the pattern of riverflow appears to influence the salinity distribution. For example, although the September 1973 and August 1974 runs were conducted at near identical Delta outflows, there was greater compression of the 2-25 millimho/cm (EC) water mass in 1973. The 2 millimho/cm EC contours were at similar locations; however, there was greater intrusion of the 25 millimho/cm EC contour in 1973. There had been several months of low (down to 4,000 ft^3/s, 110 m^3/s) Delta outflow prior to the September 1973 run. In 1974 the summer Delta outflow index was high (Figure 6) partially due to large releases from Lake Oroville.

In addition to repelling salinity intrusion, high river discharges increase the vertical salinity stratification and compress the area of the mixing zone. In March 1974, there was a vertical salinity gradient of nearly 15 millimho/cm EC, whereas during August of 1977 the maximum was only about 3 millimho/cm. There was also greater compression of the 2-25 millimho/cm EC water mass at high outflows.

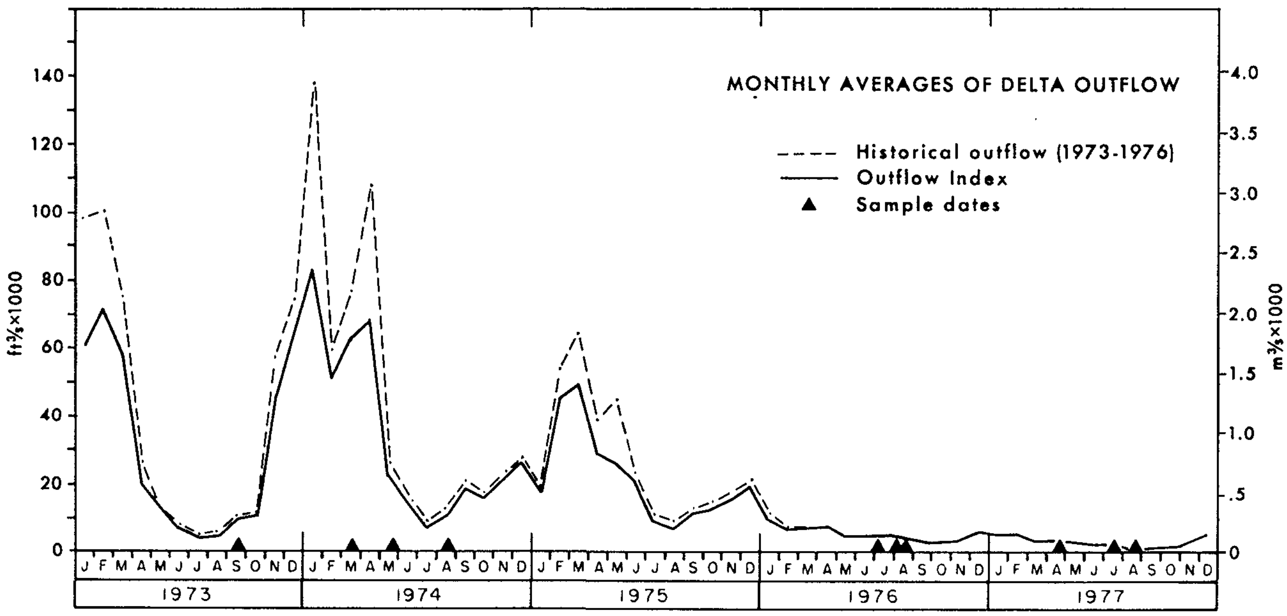

Figure 6. Comparison of the Delta outflow index and the historical Delta outflow during the study period.

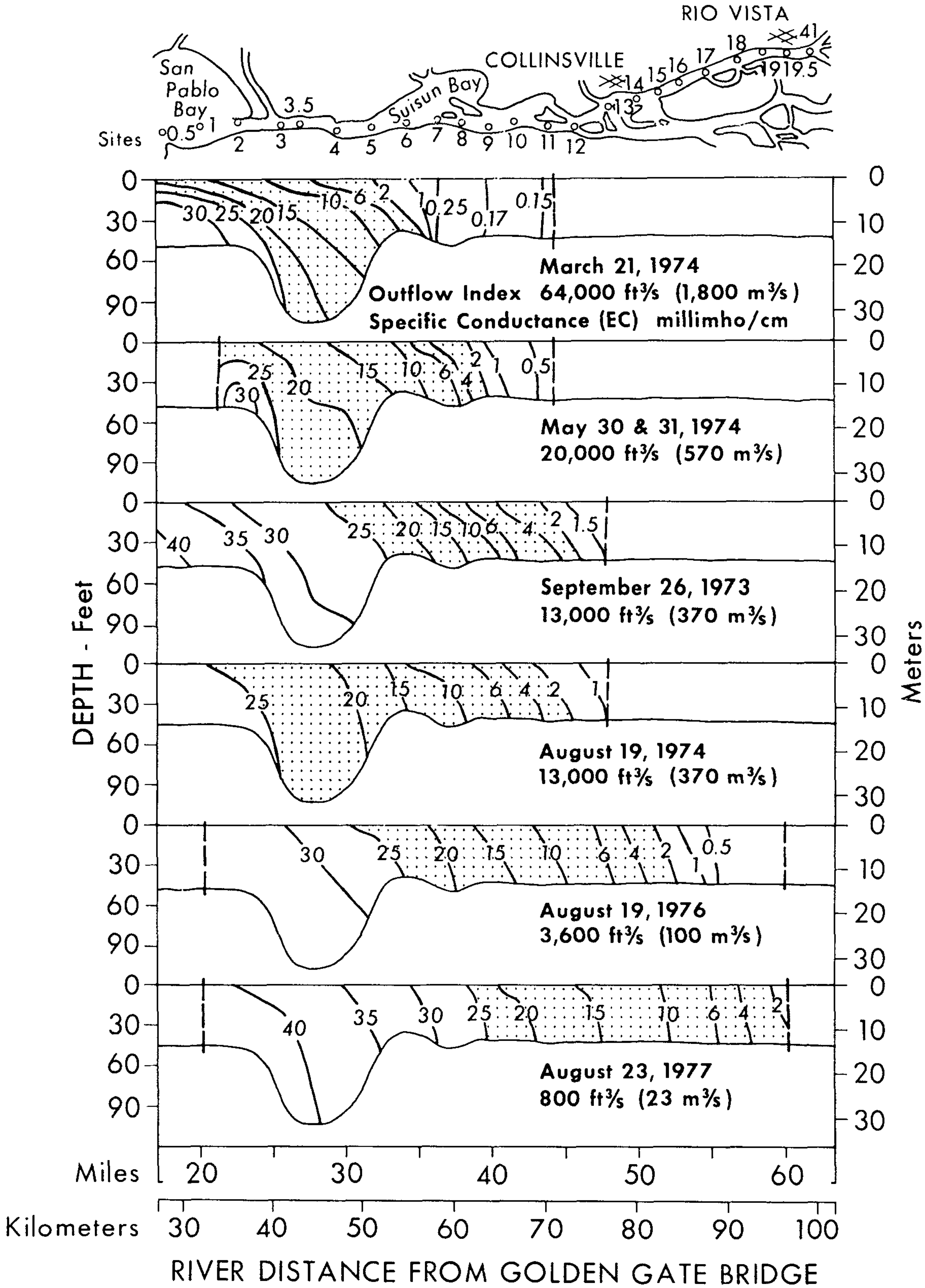

Figure 7. Isoconductivity (salinity) contours measured on high slack tides at various Delta outflows. The 2–25 millimho / cm EC range has been arbitarily shaded. Dashed vertical lines indicate the range of sites (at top of page) sampled on each servey.

TIDAL EXCURSION

Salinity intrusion varies daily with tidal excursion. The maximum tidal velocity and the height difference between the low and high tides varies with the lunar phase and regulates the distance of tidal excursion. Maximum tidal excursion occurs when tidal height differences are greatest and tidal velocities are highest.

Variations in tidal excursion are demonstrated between the August 19-21, 1974, and the August 23, 1977, data (Figures 8 and 9). The 1974 data were collected on three consecutive days with Delta outflow indices of about 13,000 ft^3/s (370 m^3/s), while the 1977 data were collected on a single day at an outflow index of 800 ft^3/s (23 m^3/s). The tidal excursion measured for the August 1974 run was nearly 6 miles (10 km). Excursion measurements were made prior to and following greater flood tides (with relative high tidal velocities) close to a spring tide. Conversely, the tidal excursion for the August 1977 run was only about 2 miles (3 km). The reduced excursion resulted from the low tidal velocities and the slight difference in tidal heights occurring on the lessor ebb near a neap tidal period.

TWO-LAYERED FLOW MODELING

The degree of salinity stratification, the pattern of sediment accumulation, and the area where sediment accumulates relative to the salinity concentration in the San Francisco Bay-Delta Estuary are very similar to what was found by Nichols and Poor (1967) in the Rappahannock Estuary on the eastern coast. Nichols and Poor attributed formation of sediment accumulation (entrapment zone) to the presence of two-layered flow. Bowden (1967) states estuaries having two-layered flow with vertical mixing generally have top to bottom salinity gradients of from 1-10 $^{o}/oo$ (1.5-15 millimho/cm EC). Salinity gradients studied in both the San Francisco Bay-Delta Estuary and the Rappanhannock Estuary fall about midway in this salinity range.

Although there are few direct measurements of two-layered flow in the upper San Francisco Bay-Delta Estuary, there is considerable indirect evidence available that two-layered flow occurs (literature review).

There were no direct measurements made of two-layered flow in the present study. However, Hydroscience, Inc., consultants to the Interagency studies, were able to mathematically replicate prototype suspended materials distribution in the study area by assuming

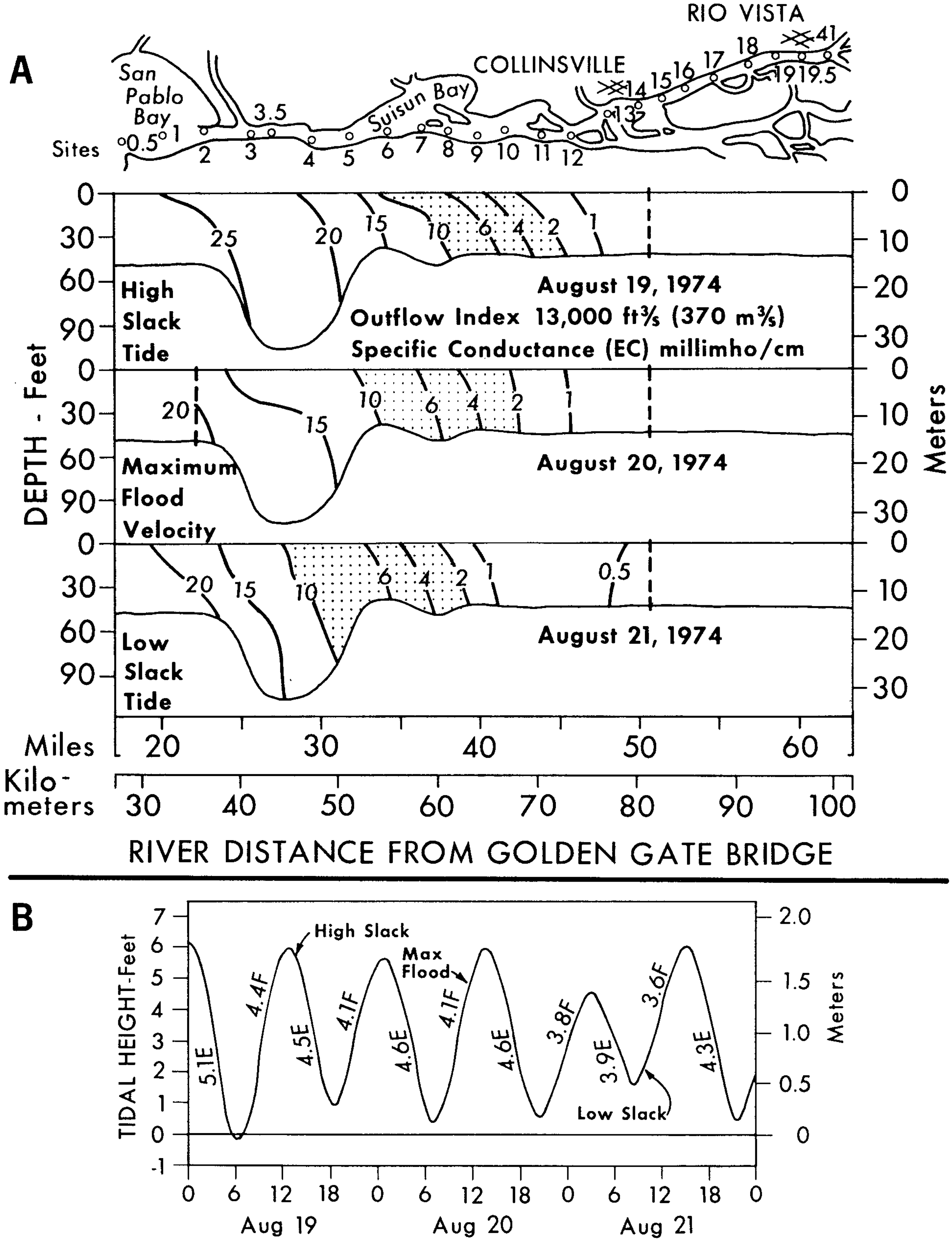

Figure 8. A, isconductivity (salinity) contours measured on three consecutive days during different tidal phases in August 1974; B, calculated Golden Gate Bridge tidal heights and maximum flood and ebb (F and E) velocities in knots.

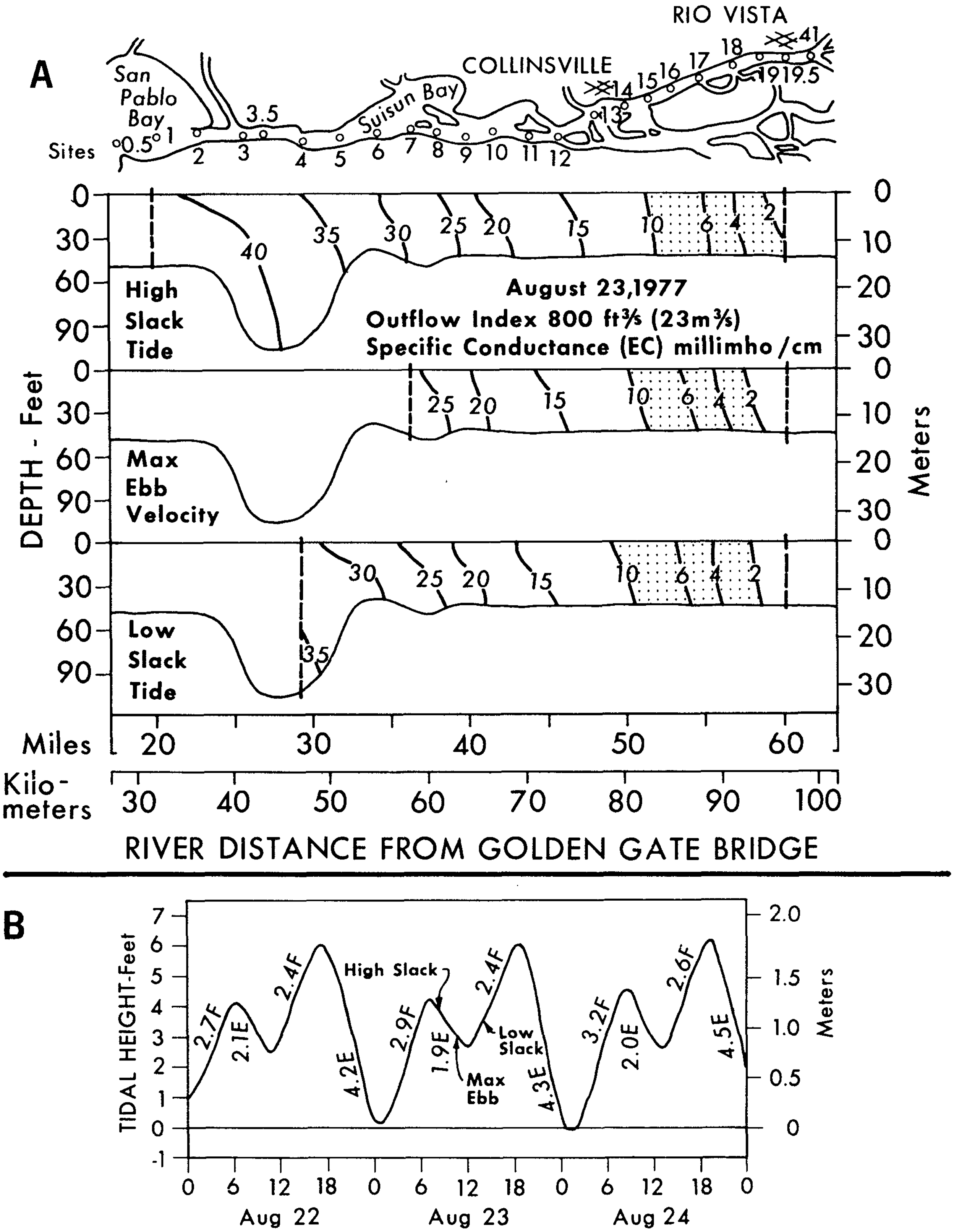

Figure 9. A, isoconductivity contours measured on three consecutive tidal phases on August 23, 1977; B, calculated Golden Gate Bridge tidal heights and maximum flood and ebb (F and E) velocities in knots.

two-layered flow circulation (O'Connor and Lung, 1977). They developed a method to compute two-dimensional (vertical) circulation patterns, utilizing data obtained in the present study.

In summary, Hydroscience, Inc., first calculated the horizontal velocities from a given salinity distribution obtained from the prototype. The model was then divided into two vertical layers by defining the plane of no-net motion from which a preliminary estimate of the associated advective and dispersive flows was determined. The salinity distribution was then calculated using the derived transport coefficients to yield the average salt content in each layer. These calculated data were then compared to the original salinity distribution. Repeated applications of the procedures produces a consistent set of transport coefficients for a particular tidal condition and freshwater flow. According to Hydroscience, Inc., this technique has been applied to a number of estuaries throughout the country with satisfactory results.

Hydroscience, Inc., (O'Connor and Lung, 1977) used the above techniques to calculate transport patterns based on data collected for the present study during September 1973 and August 1974. Figure 10 illustrates the physical dimensions, salinity, net velocities, and eddy viscosities used to calculate suspended solids distribution as illustrated in Figure 11.

PREDICTING THE ENTRAPMENT ZONE LOCATION

Evaluation of salinity and suspended materials data collected in the present study, as well as from the routine monitoring program, indicates the location of the entrapment zone can be predicted from the surface salinity. The entrapment zone location occurs in the upstream portion of the mixing zone and is typically centered where 2-10 millimho/cm EC (1-6^{o}/oo salinity) occurs in the surface water. Location of this salinity range versus the Delta outflow index as measured on high slack tides is illustrated in Figure 12. This chart could be used to roughly estimate the location of the entrapment zone at other outflows within the range presented. However, as previously discussed, the pattern and duration of Delta outflow, the accuracy of the estimated Delta outflow, and the tidal height all influence salinity intrusion.

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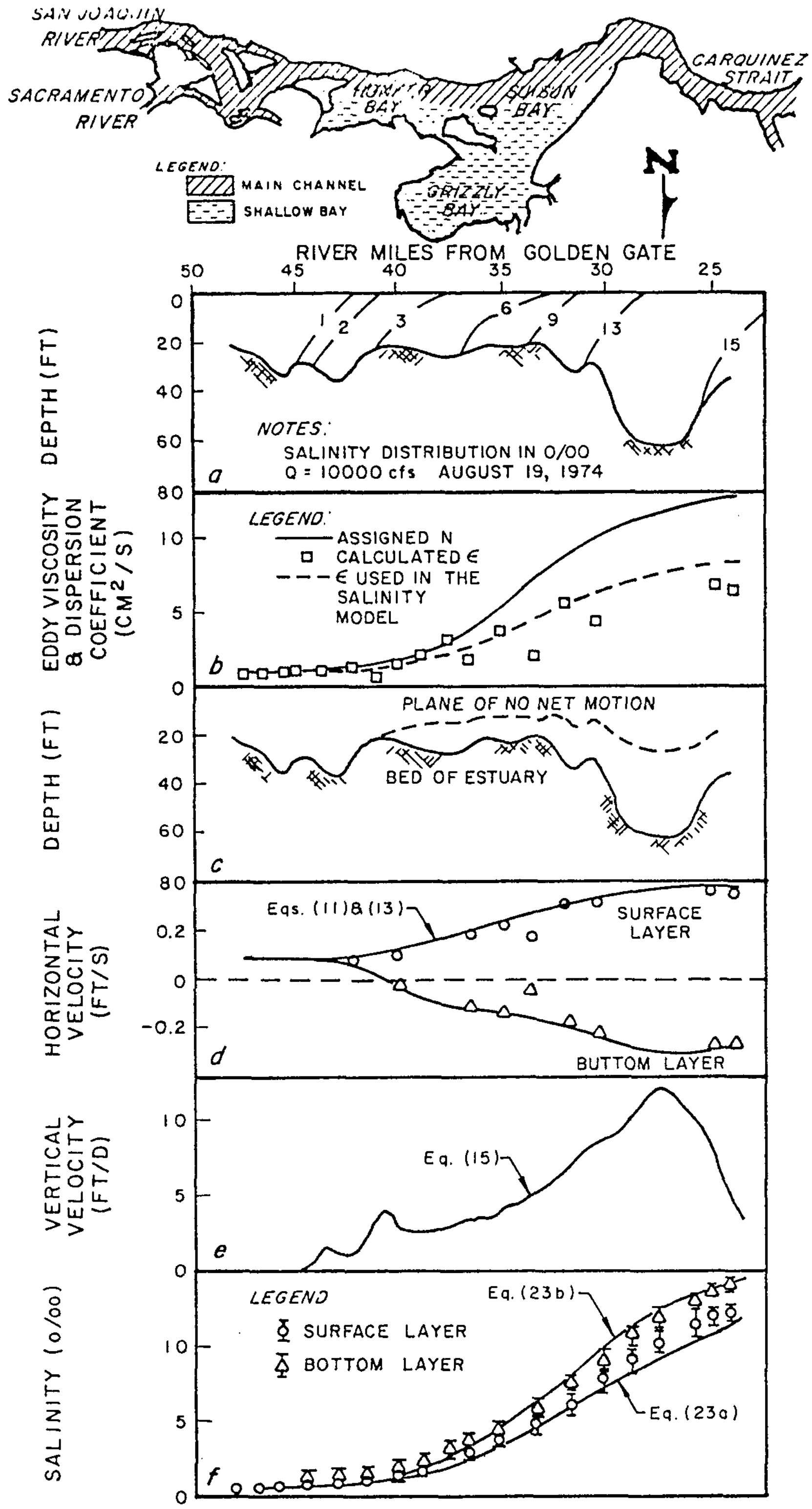

FIGURE IV-3

SALINITY CALCULATION FOR SACRAMENTO-SAN JOAQUIN ESTUARY (AUGUST, 1974)

Figure 10. Figure IV–3, from Hydroscience, Inc. (O'Connor and Lung, 1977), illustrating the physical dimensions, salinity, net velocities, and eddy viscosity coefficients used to simulate suspended solids distribution in the upper estuary. Points represent field data. Lines represent simulations except salinity which were determined from field data. (see O'Connor and Lung, 1977, for equations).

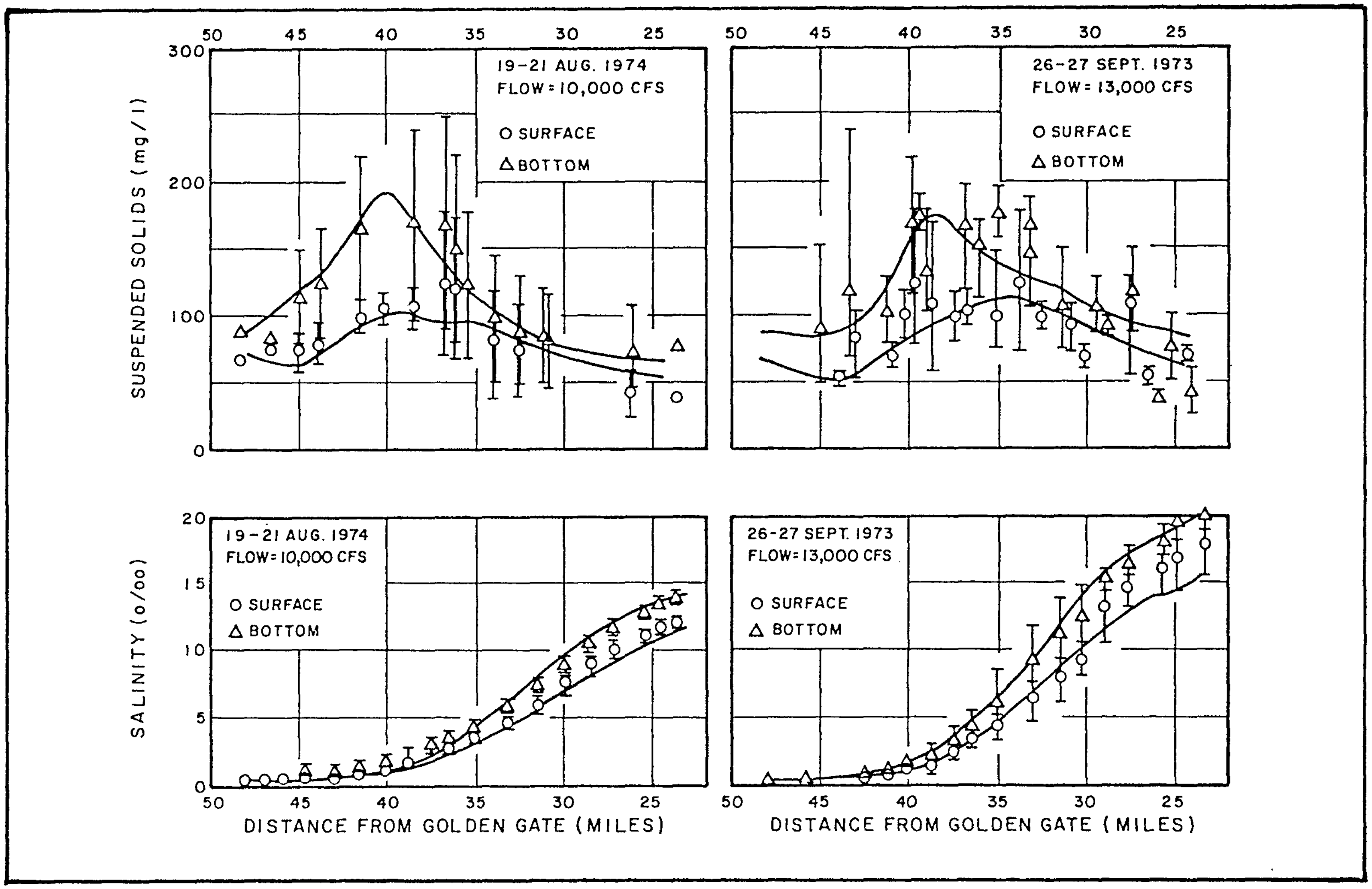

FIGURE V-3
SUSPENDED SOLIDS CALCULATION FOR SACRAMENTO-SAN JOAQUIN ESTUARY
(AUGUST, 1974 AND SEPTEMBER, 1973)

Figure 11. Figure V – 3, from Hydroscience, Inc. (O'Connor and Lung, 1977), illustrating both simulate and prototype distributions of suspended solids and salinity in the upper estuary. (see O'Connor and Lung, 1977, for equations).

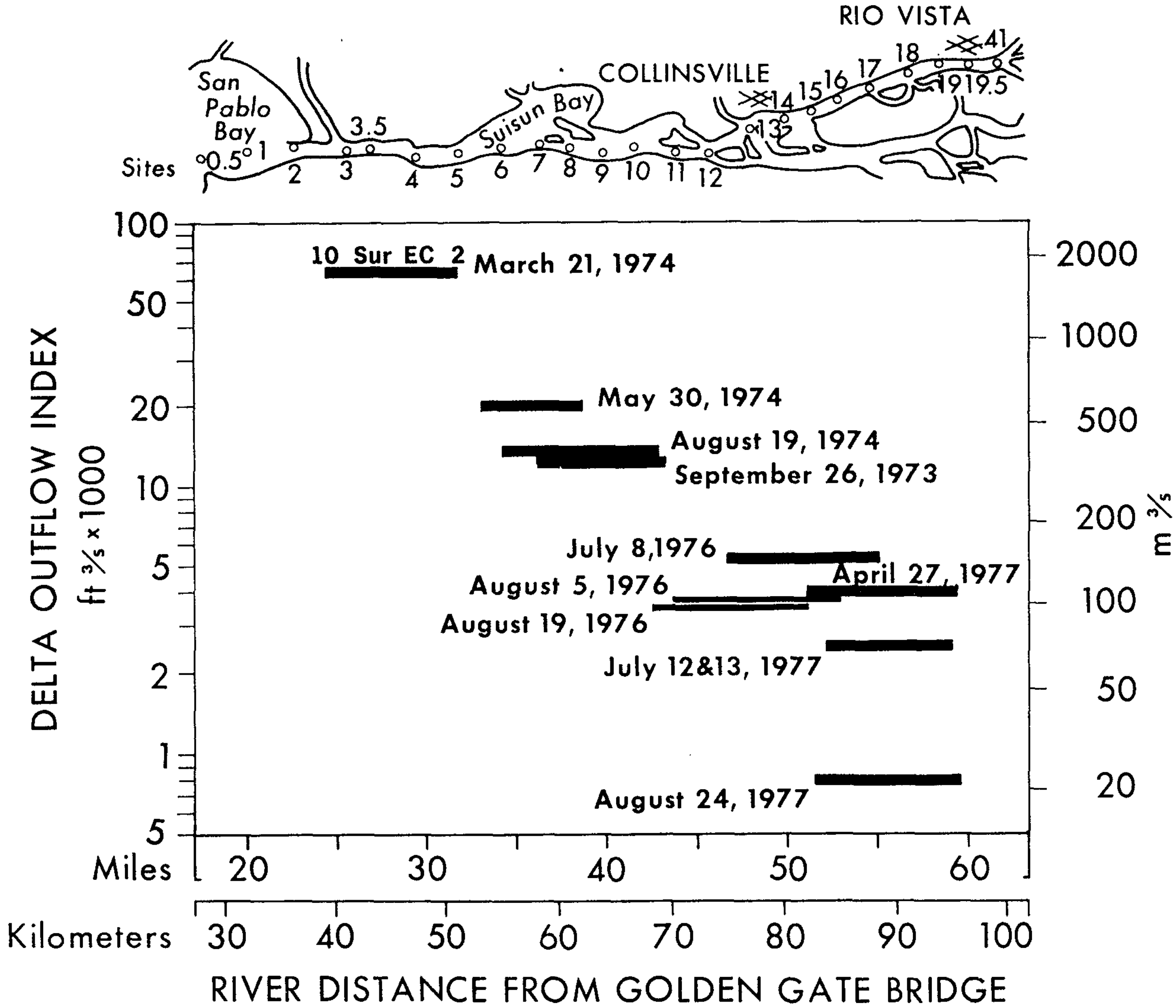

Figure 12. Estimated high slack tide locations of the entrapment zone, based on the 3-foot depth 2 – 10 millimho / cm EC (1 – 6 ⁰/oo salinity) range at various Delta outflows.

Distribution of Constituents in the Sacramento River

Areas of maximum suspended materials (including certain estuarine biota) accumulation were evident at all of the outflows studied. In general, the concentration of suspended materials in the entrapment zone varied directly with Delta outflow and with tidal velocity.

Turbidity and total suspended solids (TSS) are both measurements of suspended materials. Turbidity, however, is a measure of the light scattered by suspended material while TSS is a measure of the concentration by weight. Relationships between these two parameters vary with seasonal changes. Phytoplankton, most detrital organic materials, and larger inorganic materials scatter lesser amounts of light relative to their weight as compared to very fine inorganic materials. For example, in the Bay-Delta Estuary, high turbidities during the winter may be due almost entirely to suspension of very small-diameter inorganic materials. However, in the summer, high concentrations of plankton, detrital organic material, and larger-diameter inorganic materials contribute more significantly to the turbidity measurements than in the winter.

For this study, a combination of measurements, chlorophyll, phytoplankton, zooplankton, turbidity, and TSS were used to differeniate between the varying suspended materials.

Throughout the seasons, the maximum concentration of suspended materials in the entrapment zone varied significantly from the upstream and downstream concentration and with depth.

SUSPENDED SOLIDS AND TURBIDITY

Areas of maximum suspended materials concentrations, measured as turbidity and TSS were observed on each of the sampling runs (Figures 13 and 14). Typically these areas were centered in the 2-10 millimho/cm EC (1-6 $^{o}/oo$) surface water. The TSS in the entrapment zone varied from 2-40 times the upstream and downstream concentrations and increased up to 20 times in concentration with depth. Because of the time required for TSS analyses and the good correlation between TSS and turbidity, in 1976 and 1977 only a limited number of TSS samples were collected. The 1976 and 1977 TSS data are therefore not illustrated in Figure 14.

The maximum turbidity measured (over 800 FTU's) was centered in Carquienz Strait during the highest Delta outflow index studied

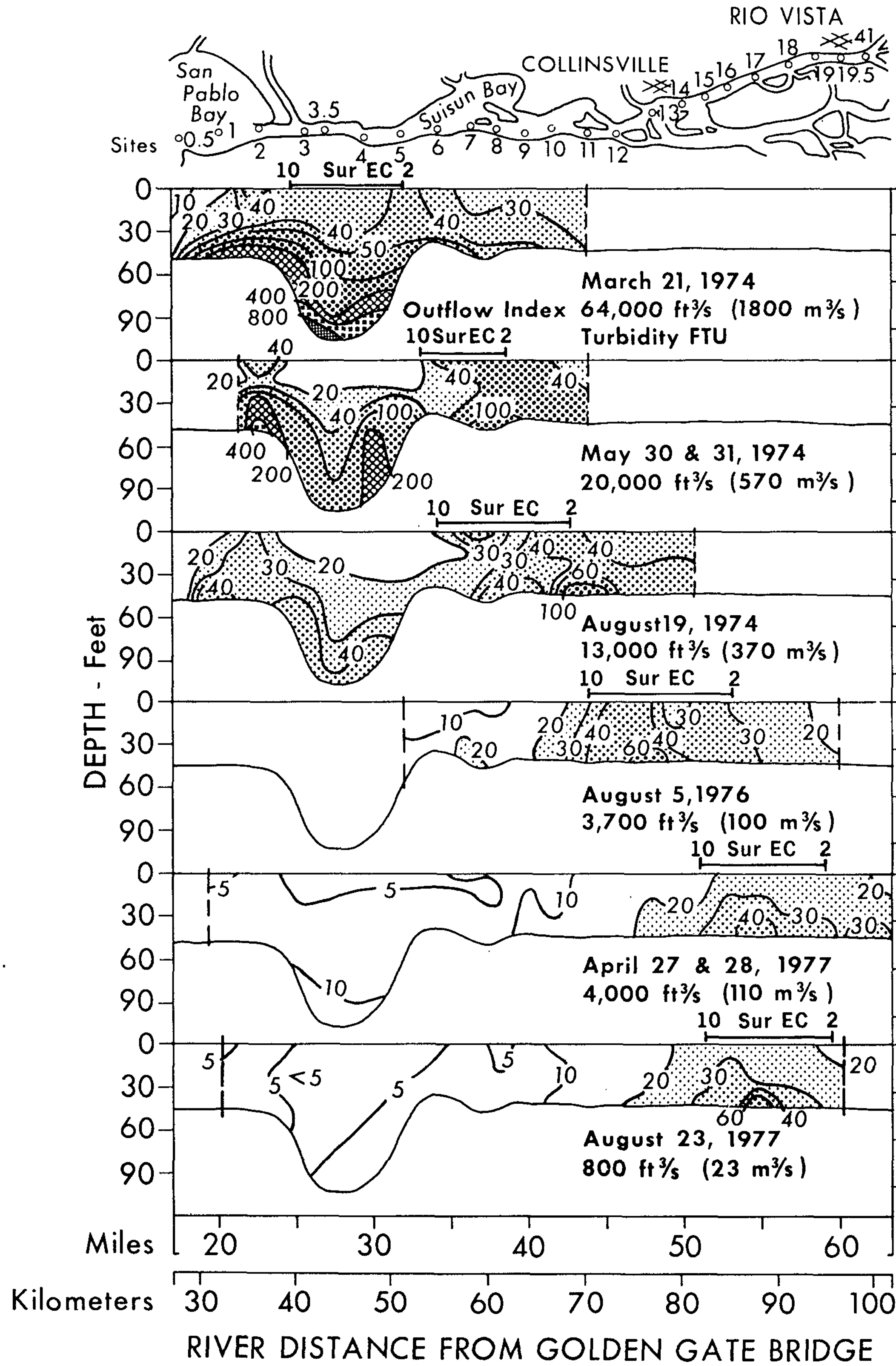

Figure 13. Distribution patterns of turbidity relative to salinity on high slack tides at various Delta outflows.

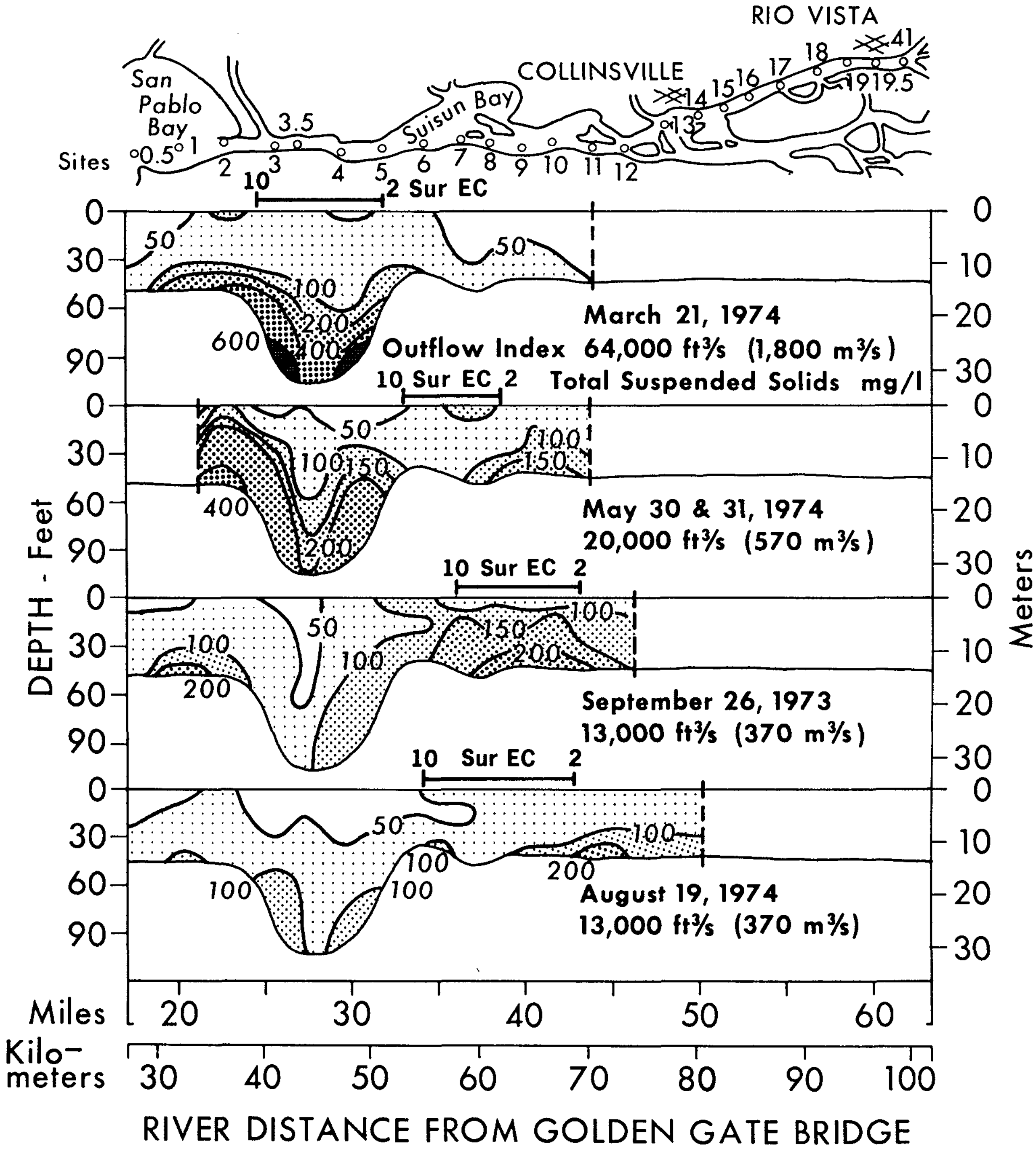

Figure 14. Distribution patterns of suspended solids relative to salinity on high slack tides at various Delta outflows.

(64,000 ft^3/s or 1,800 m^3/s). In 1977 when the Delta outflow index dropped to 800 ft^3/s (23 m^3/s), the entrapment zone was centered nearly 30 miles (48 km) upstream and maximum turbidities were down to about 60 FTU's.

Volatile Suspended Solids (VSS) were routinely analyzed along with the TSS. The VSS concentration throughout the study was generally between 10 and 20 percent of the TSS.

Other factors in addition to the net two-layered flow estuarine circulation pattern influenced the quantity of TSS entrapped. These include the riverborne suspended sediment load; flocculation, aggregation and settling rates; tidal and wind turbulence; estuarine topography; and dredging.

Riverborne Suspended Materials Load

High suspended sediment loads typically occur with floods during winter months and to a lesser extent in the late fall and early spring. In recent years the regulation of flows by reservoirs have reduced winter and spring riverflows and increased riverflows throughout the summer and fall. The regulated flows contain a reduced suspended sediment load as a result of settling that occurs in the reservoirs. Regulated releases and drainage return flows, however, have greatly increased the summer flows and suspended sediment loads.

Figure 15 illustrates the suspended sediment discharge in the Sacramento River at Sacramento and in the San Joaquin River at Vernalis. These are the two main river systems discharging to the Delta. The combined discharge is an estimate of the total suspended sediment load, however, during flooding and very high outflows, suspended sediment discharge to the Delta from the Yolo Bypass may be equal to or even greater than the above river discharge. Since the discharge from the Yolo Bypass is not measured, the total discharge to the Delta is underestimated.

The entrapment zone was located further seaward and with higher concentrations of suspended solids during periods of high suspended sediment discharge as compared to periods of low suspended sediment discharge (Figures 13 and 14). These data seem to support Postma's (1967) statement that the magnitude of the turbidity maximum (entrapment zone) is a direct function of, first, the amount of suspended matter in the river or sea and, second, the strength of the estuarine current.

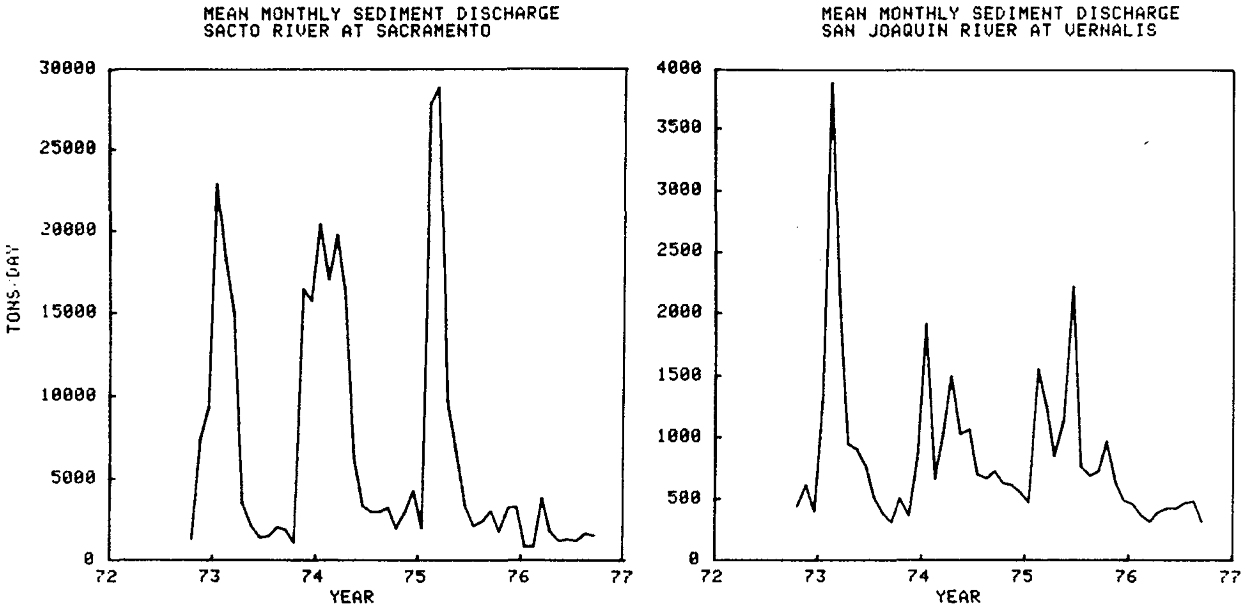

Figure 15. Suspended sediment loads to the Delta: A, Sacramento River at Sacramento; B, San Joaquin River at Vernalis. (Note, tons / day scale is different for the two rivers.)

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The location of the maximum suspended solids occurred in higher salinity water during high outflows than during low outflows (Figures 13 and 14). This may have resulted from a couple of factors. First, the winter temperatures increase the water viscosity and reduce the settling rates. Second, the greater net downstream velocity in the upper layer during high flows may carry the settleable suspended materials farther downstream and into more saline water before flocculation, aggregation, and settling occurs.

There are different opinions as to what will happen to the water transparency in Suisun Bay as increasing amounts of sediment are diverted from the estuary under future water development. One opinion is the transparency is inversely correlated to the sediment load entering the estuary during any given year; therefore, transparencies would increase with decreasing loads. Conversely, a second opinion is wind and tidal sediment resuspension of the vast quantities of deposited materials in the estuary along with tidal dispersion will maintain fairly constant transparency in the Suisun Bay area for many years of low river inflow.

Summer Suisun Bay secchi disc measurements (made monthly from 1968-1971 and twice monthly from 1972-1977) by the DFG, as well as turbidity measurements in this study, have demonstrated a pronounced increase in transparencies during the two consecutive lowest outflow years 1976 and 1977 since project operation began. This inverse relationship between the average water transparency at 17 Suisun Bay area sites and the summer Delta outflow is demonstrated in Figure 16.

This relationship suggests the summer water transparency in Suisun Bay is strongly influenced by the Delta outflow which also regulates the entrapment zone location. The farther the entrapment zone moves upstream with salinity intrusion the more transparent the Suisun Bay area becomes. Even though summer wind and tidal resuspension forces were considered to be about equal each summer, considerable transparency variation occurred between 1968 and 1977. In addition to outflow, other factors were also thought to influence the summer variation in transparency. These include the winter sediment load, the summer sediment load, and the summer inflow sediment concentration.

Within the entrapment zone (2-10 millimho/cm EC), the factors thought to influence the summer water transparency included the winter suspended sediment load, summer suspended sediment load, the summer suspended sediment concentration entering the Delta, and the location of the entrapment zone relative to the shallow bays. To evaluate the first three factors routine secchi disc measurements made by the DFG in waters within the 2-10 millimho/cm EC range (from

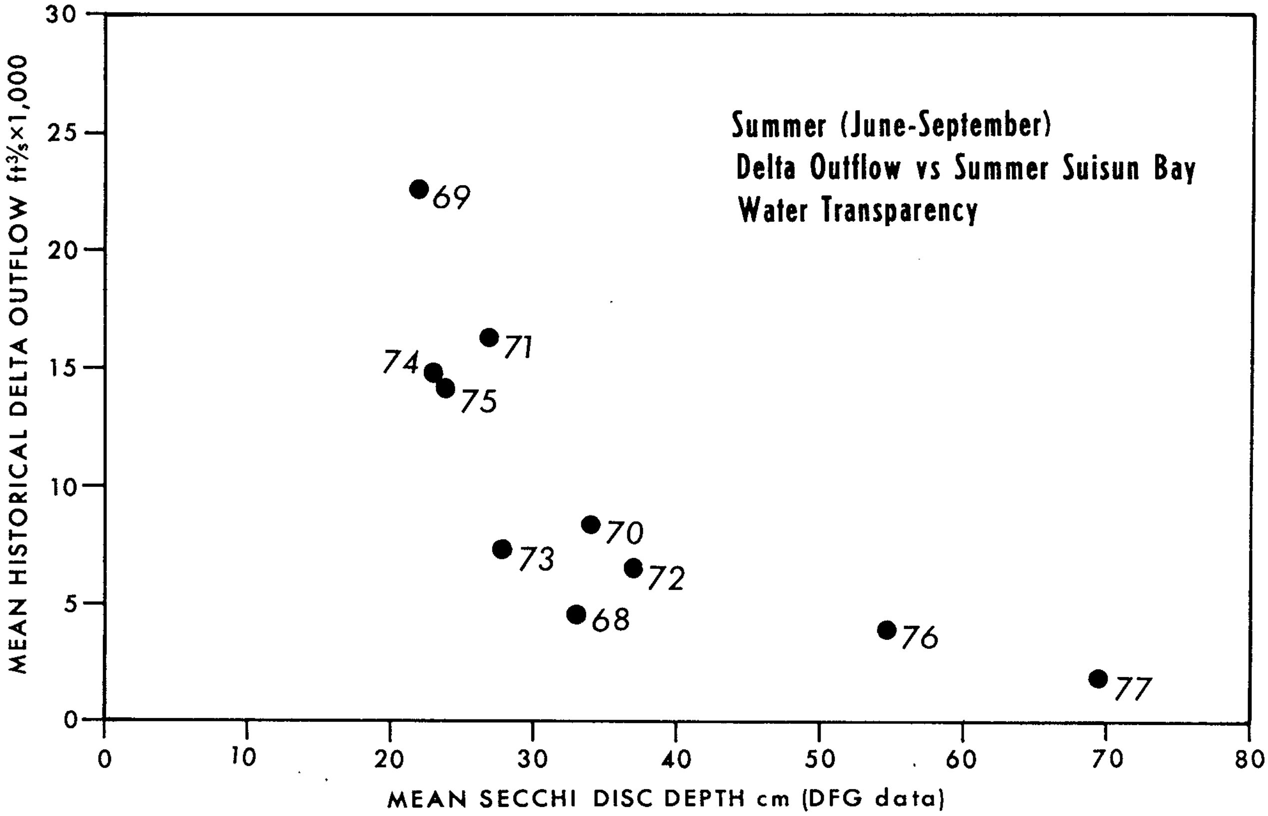

Figure 16. Summer Suisun Bay water transparency versus summer historical Delta outflow. (The 1977 outflow value was calculated as the Delta outflow index).

14 channel sites between Rio Vista and Martinez) were averaged for each summer (June-September) and compared with the winter suspended sediment load (Figure 17), summer suspended sediment load (Figure 18), and summer suspended sediment concentration (Figure 19). The suspended sediment load and concentration data were collected in the Sacramento River at Sacramento by the USGS (data were not available for 1977 or for the Yolo Bypass). There appears to be a slight inverse relationship between the summer transparency and the above factors; however, the relationships are not conclusive. The summer suspended sediment load and concentration were related to the winter load. This primarily occurs because, typically, high summer outflows follow high winter outflows.

One can speculate that when the entrapment zone is located adjacent to the shallow bays (where wind and tidal resuspension is greatest), the water transparency may decrease in the entrapment zone. This relationship was not evaluated, however.

Flocculation, Aggregation, and Settling

Laboratory tests (Arthur, 1975) using Sacramento River water in which the salinity was adjusted with concentrated seawater brine from San Francisco Bay demonstrated that flocculation, aggregation, and increased settling rates occur at specific conductances above 1 millimho/cm (0.6 $^{o}/oo$). An example of laboratory particle aggregation induced by the addition of seawater brine to Sacramento River water collected during flood stage is illustrated in Figure 20.

Field measurements were initiated in 1975 to obtain settling rate data for verification of the Hydroscience suspended solids model. Samples were collected with a submersible pump and stored in barrels for transport back to the field laboratory. At the laboratory the samples were stirred, then pumped into settling chambers 6 feet tall and 8 inches in diameter with sampling ports at 1-foot intervals. Changes in concentration at each port were measured periodically to determine settling rates.

Dr. R. Krone, University of California at Davis, contended that pumping the sample disrupted particle aggregation resulting in erroneous settling rates (personal communication). He designed and built a combination water sampler-settling chamber 3 inches in diameter, 1 meter long, with directional fins on one end, and sampling ports at 1-foot intervals. This device was lowered horizontally to the desired water depth. Sufficient time was allowed to flush the

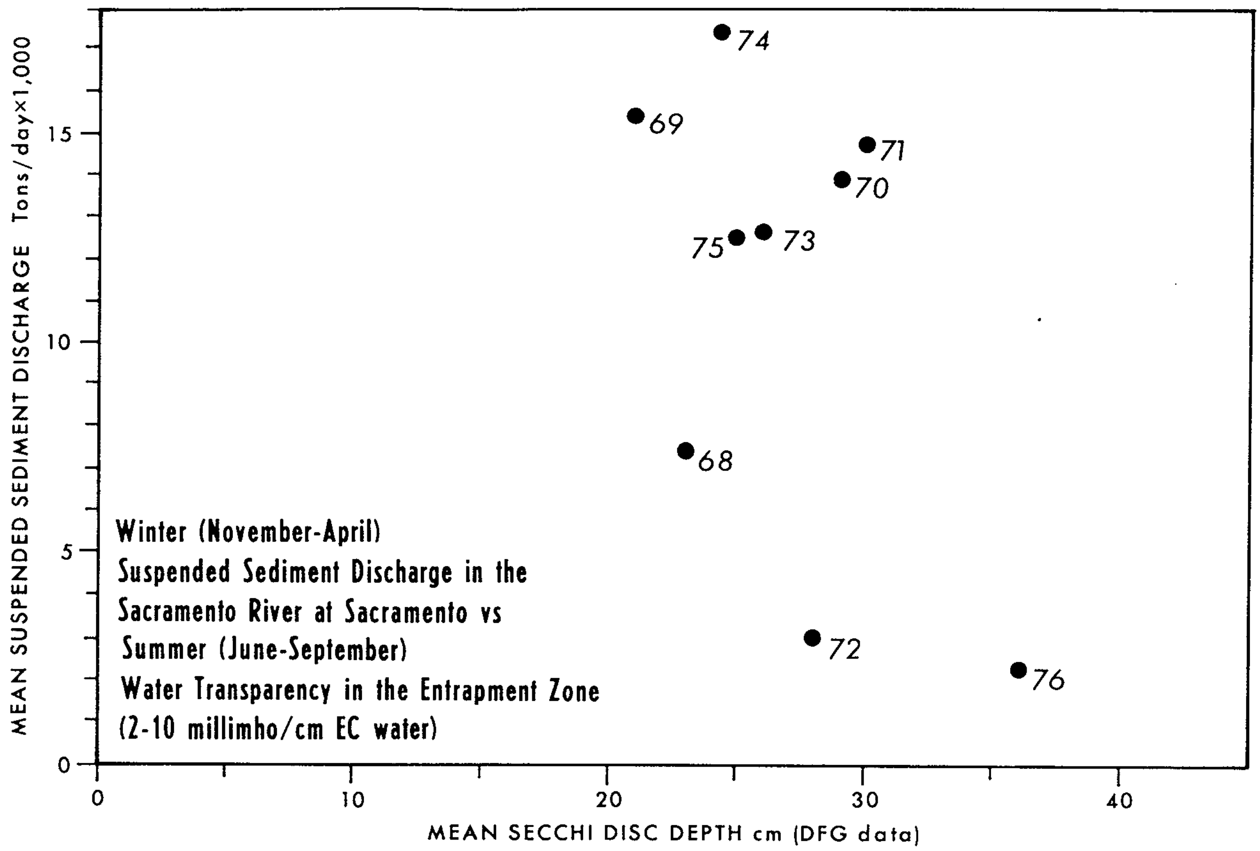

Figure 17. Summer water transparency in the entrapment zone (2–10 millimho / cm EC range) versus winter suspended sediment load at Sacramento.

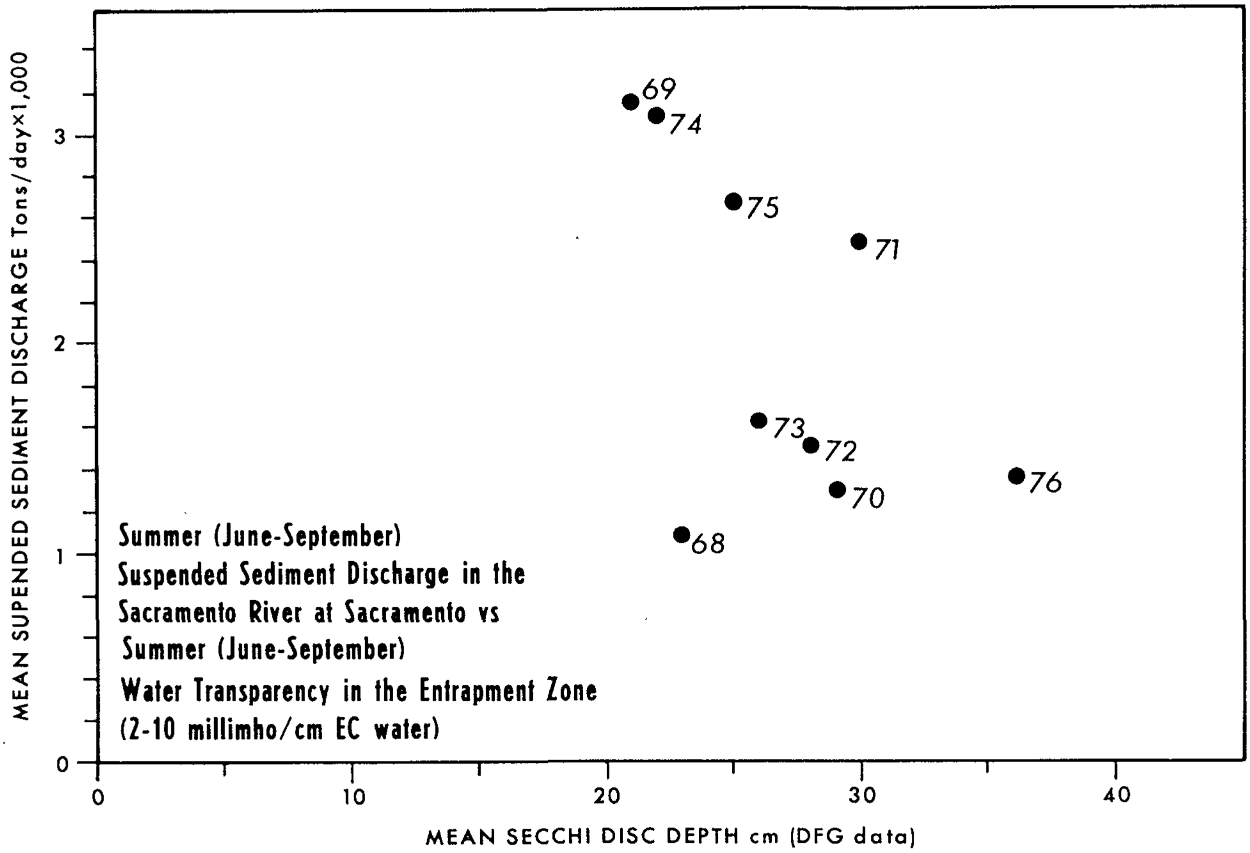

Figure 18. Summer water transparency in the entrapment zone (2–10 millimho / cm EC range) versus summer suspended sediment load at Sacramento.

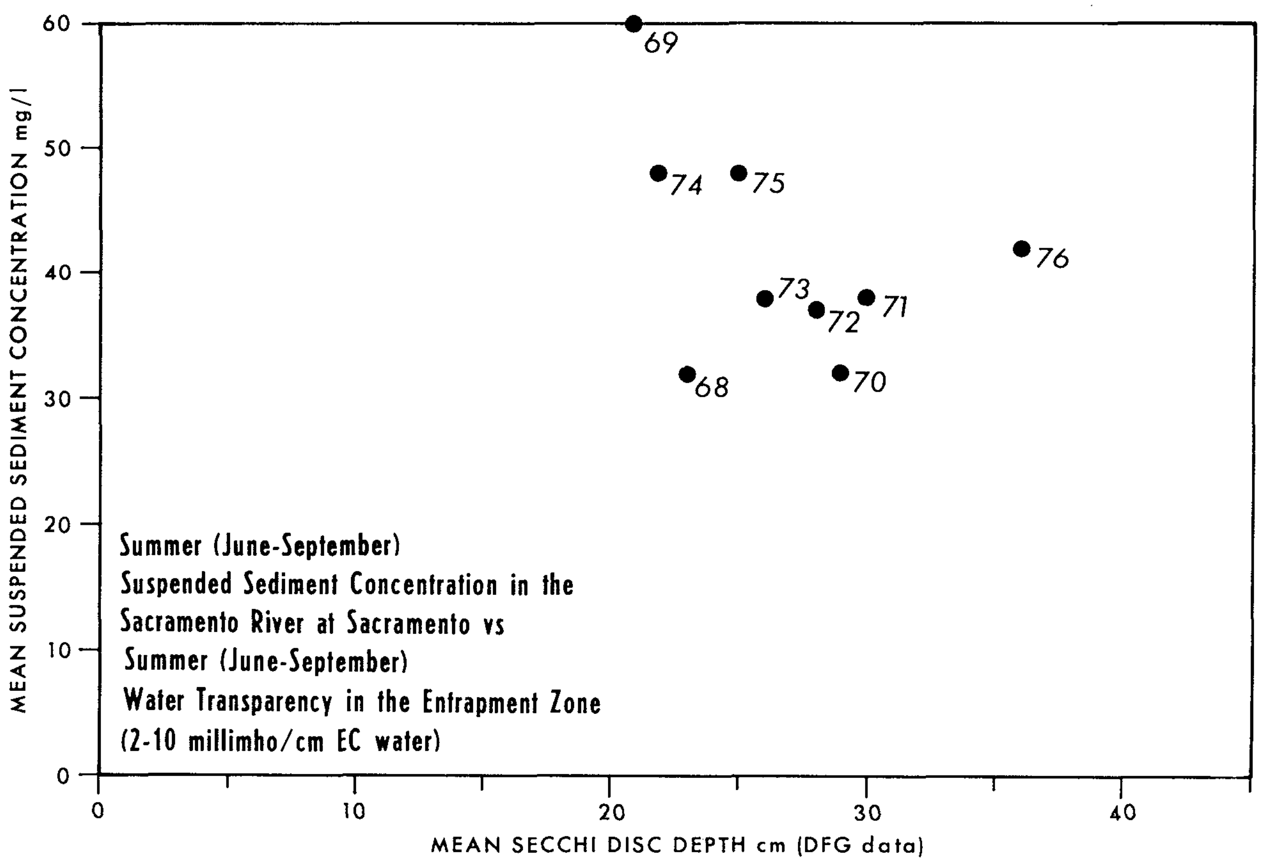

Figure 19. Summer water transparency in the entrapment zone (2–10 millimho / cm EC range) versus summer suspended sediment concentration at Sacramento.

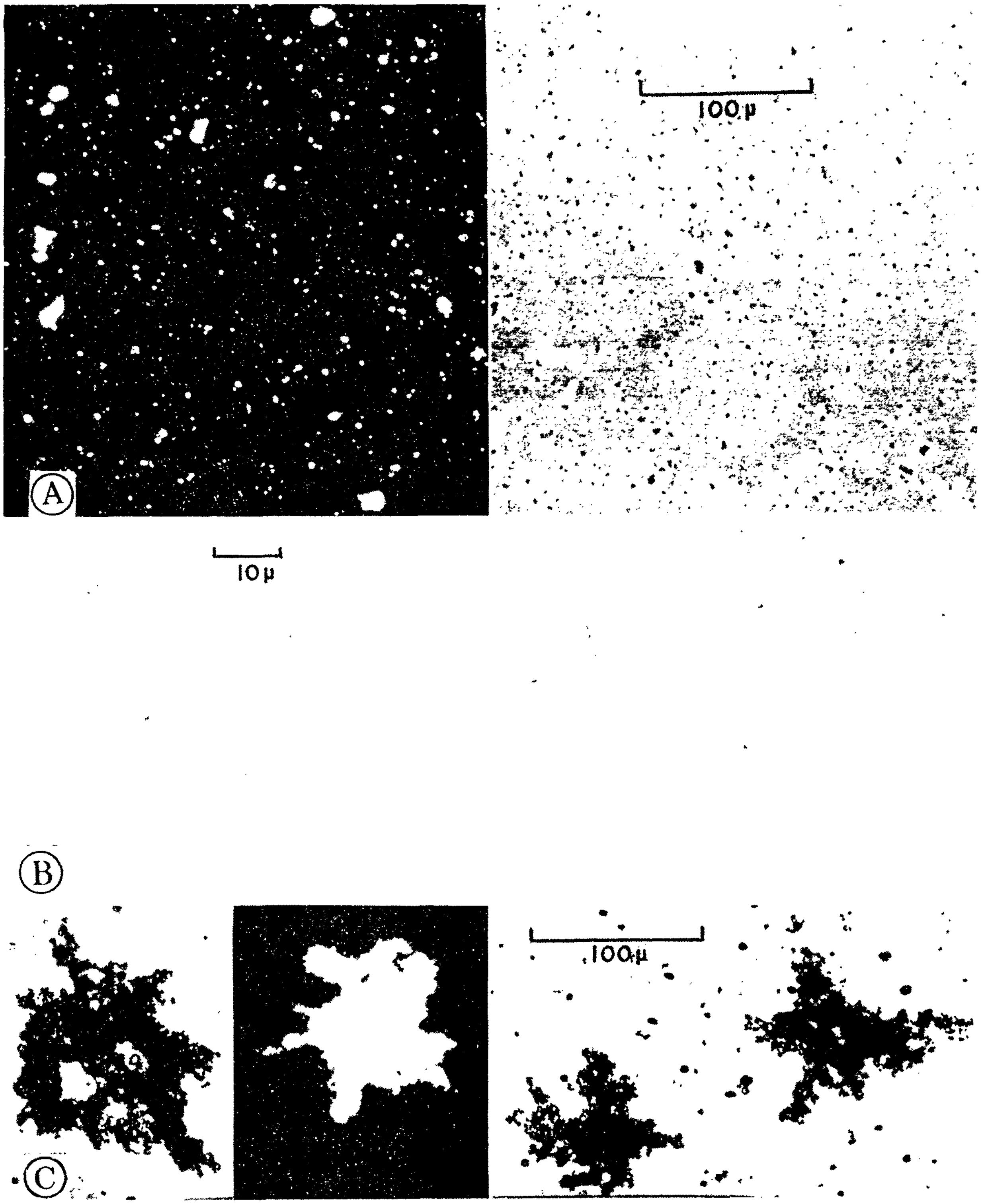

Figure 20. Photomicrographs illustrating laboratory induced flocculation of suspended sediments collected from the Sacramento River during flooding conditions on March 25, 1975: A, control (0.12 millimho / cm EC); B, control (0.12 millimho / cm EC) (enlarge); C, after addition of concentrated sea brine (2.5 millimho / cm EC in beaker) and 8 hours of stirring at 30 rpm.

chamber. Then a messenger was released to close the ends of the chamber. The sampler was raised to the surface, rotated, and hung vertically on board the boat. Samples were collected periodically from the sampling ports for settling rate measurements.

These two types of settling chambers and methods of collection were compared in 1977. Settling rates were highest in water samples collected and settled in Dr. Krone's chambers. The rates were several times less in samples collected by submersible pump and settled in both the large chambers and Dr. Krone's chambers. The reduced settling rates in the pumped samples suggested deaggregation of particles occurs with the high turbulence created by pumping, implying prior flocculation and/or aggregation had occurred (USBR unpublished data).

Increased surface transparencies occur with distance downstream of the entrapment zone. This is thought to be due, in part, to the settling of suspended material with settling velocities greater than the upward vertical velocity of the water. Also downstream of the entrapment zone there is increasing dilution with low-turbidity seawater. The combined effect of the above, has not been quantified.

The extent to which flocculation increases the settling rates of suspended materials and the quantity of suspended materials observed in the entrapment zone is uncertain. However, the evaluation of laboratory and field data suggests it probably is an important factor influencing the spatial distribution and entrapment of suspended materials. Postma (1967) states that for many years flocculation has been suggested as contributing to the turbidity maximum.

Tidal, Wind, and Dredging Resuspension

Resuspension induced by wind, tide, and dredging action results in the continual relocation of a portion of the deposited sediments. It has been observed in this study and in the routine water quality program that TSS concentrations and turbidity in the shallow areas of Suisun and San Pablo Bays have more than doubled (Rumboltz, et al., 1976) following periods of high wind such as pictured in Figure 21.

Increasing tidal velocities also increase the rate of sediment resuspension. Masses of highly turbid water several feet in diameter have often been observed on calm days to come billowing to the surface with increasing tidal velocities as depicted in Figure 21.

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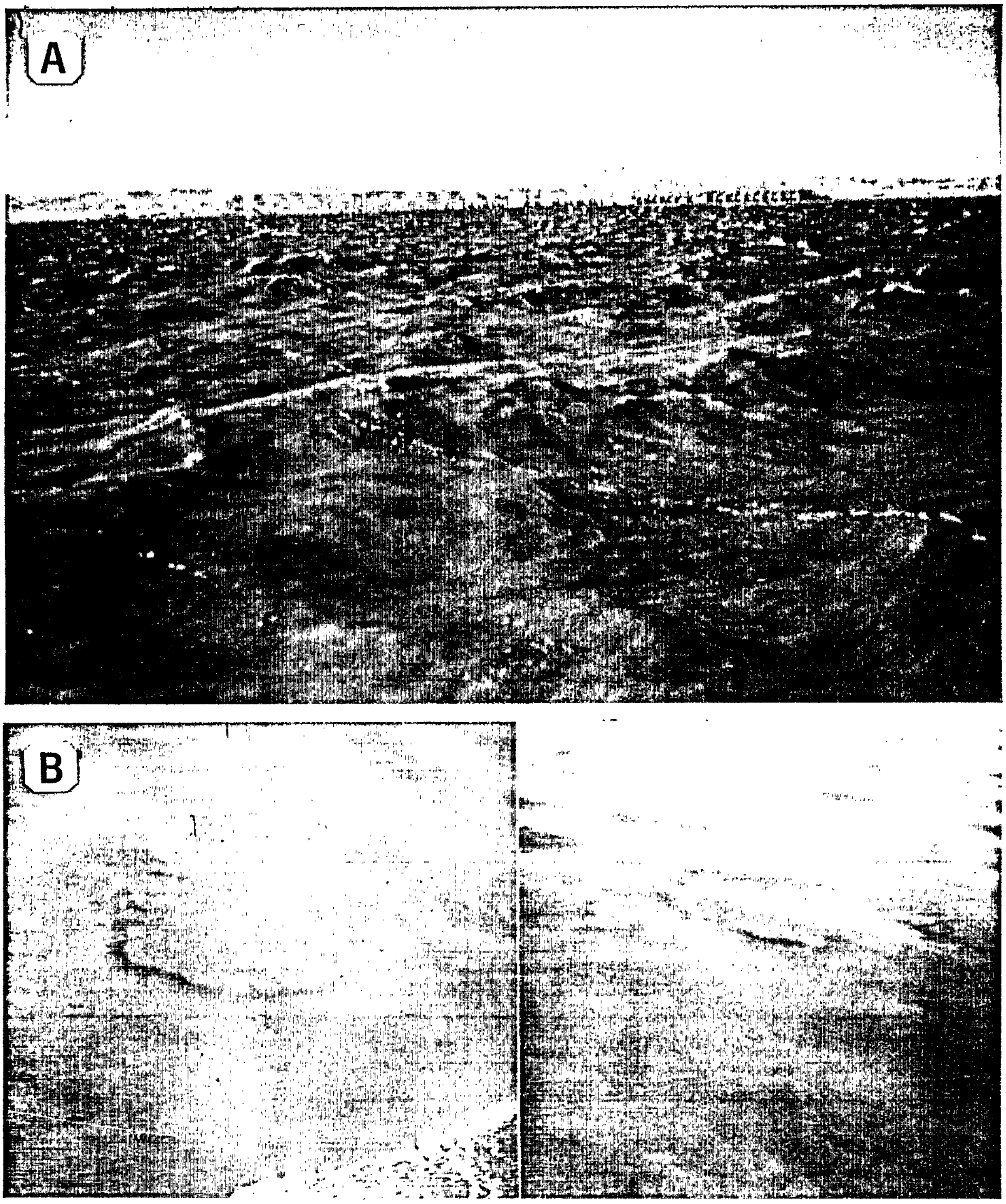

Figure 21. Examples of sediment resuspension in Grizzly Bay: A, during periods of high winds; B, with increasing tidal velocity.

Differences in the amount of resuspension and settling were observed between greater and lesser flood or ebb tides. The greatest resuspension of materials (between slack water and maximum tidal velocity) was observed when tidal height differences and maximum velocities were high (Figure 22) as opposed to when they were low (Figure 23).

Dredging also tends to relocate as well as resuspend sediments (Figure 24). The most intense dredging in the estuary occurs in Mare Island Strait just off Carquinez Strait, and the spoils are deposited in San Pablo Bay.

The estuarine tidal circulation of the resuspended sediment (Figure 24) is another feature that can contribute suspended material to the entrapment zone. Once in the channel, this material may settle into the lower layer where it can be transported upstream to the entrapment zone or laterally where it may settle in areas where reduced wave and/or tidal action no longer resuspend it.

The maximum concentration of TSS observed was over 2,500 mg/l and occurred at the strength of flow on a floodtide during a period of high Delta outflow (Figure 25). During high slack water on the previous day, only about one-third of the maximum concentration was observed.

It was not determined what percentage of the suspended materials transported to the entrapment zone were attributed to tidal, wind, and/or dredging resuspension.

Bathymetry

The effect of estuarine circulation on suspended sediment distribution is greatly influenced by bathymetry (channel depth and configuration). This is especially evident in the San Francisco Bay-Delta Estuary, which is a series of shallow bays connected by deeper channels. As previously mentioned, settled materials are resuspended and transported from one area to another by riverflow, resuspension, and estuarine circulation. Resuspension, transport, and deposition of these materials are greatly influenced by channel width and depth. An example of the effect of bathymetry is discussed by Mead (1972) for the Carquinez Strait area.

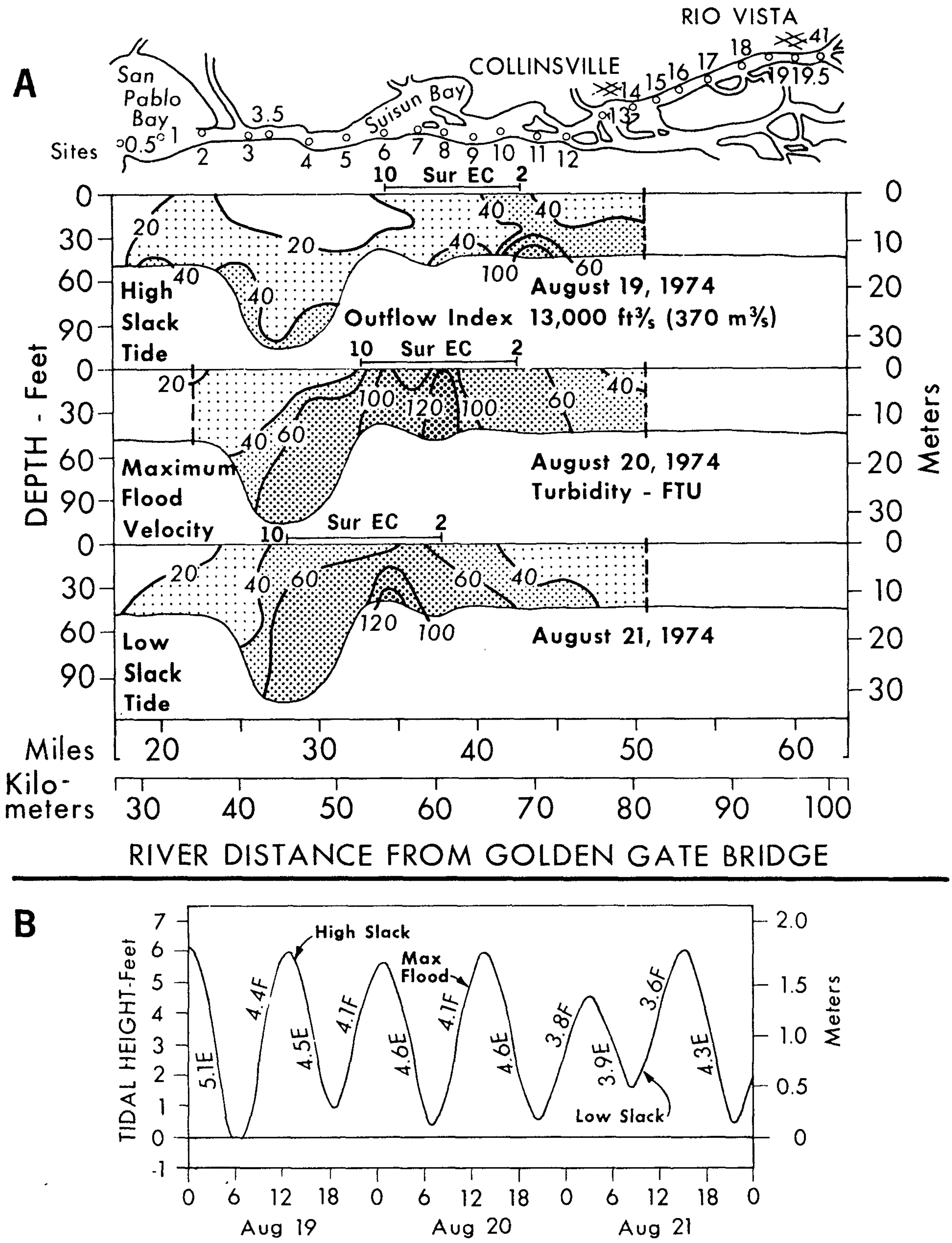

Figure 22. A, distribution patterns of turbidity relative to salinity measured on three consecutive days during different tidal phases in August 1974; B, calculated Golden Gate Bridge tidal heights and maximum flood and ebb (F and E) velocities in knots.

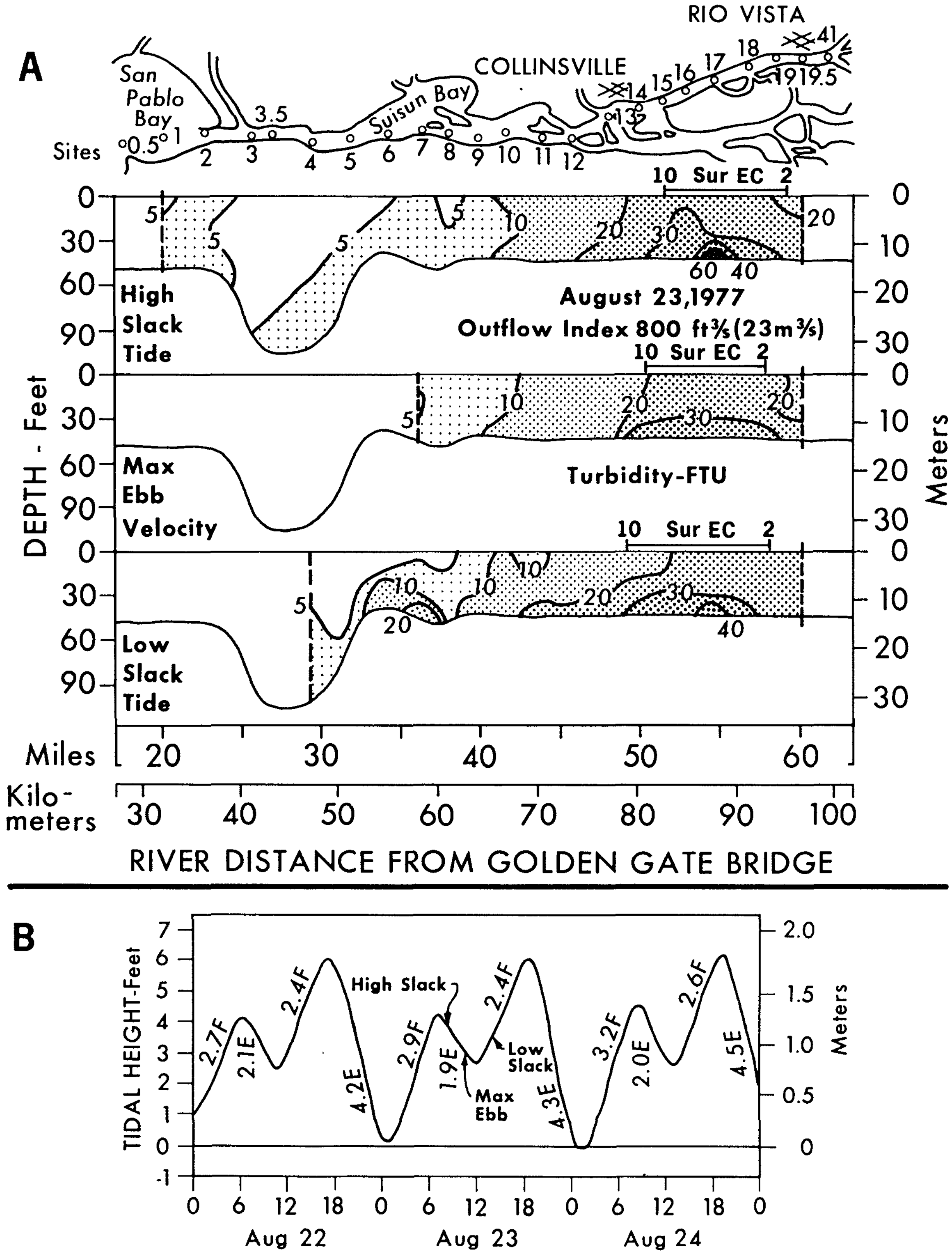

Figure 23. A, distribution patterns of turbidity relative to salinity measured on three consecutive tidal phases on August 23, 1977; B, calculated Golden Gate Bridge tidal heights and maximum flood and ebb (F and E) tidal velocities in knots.

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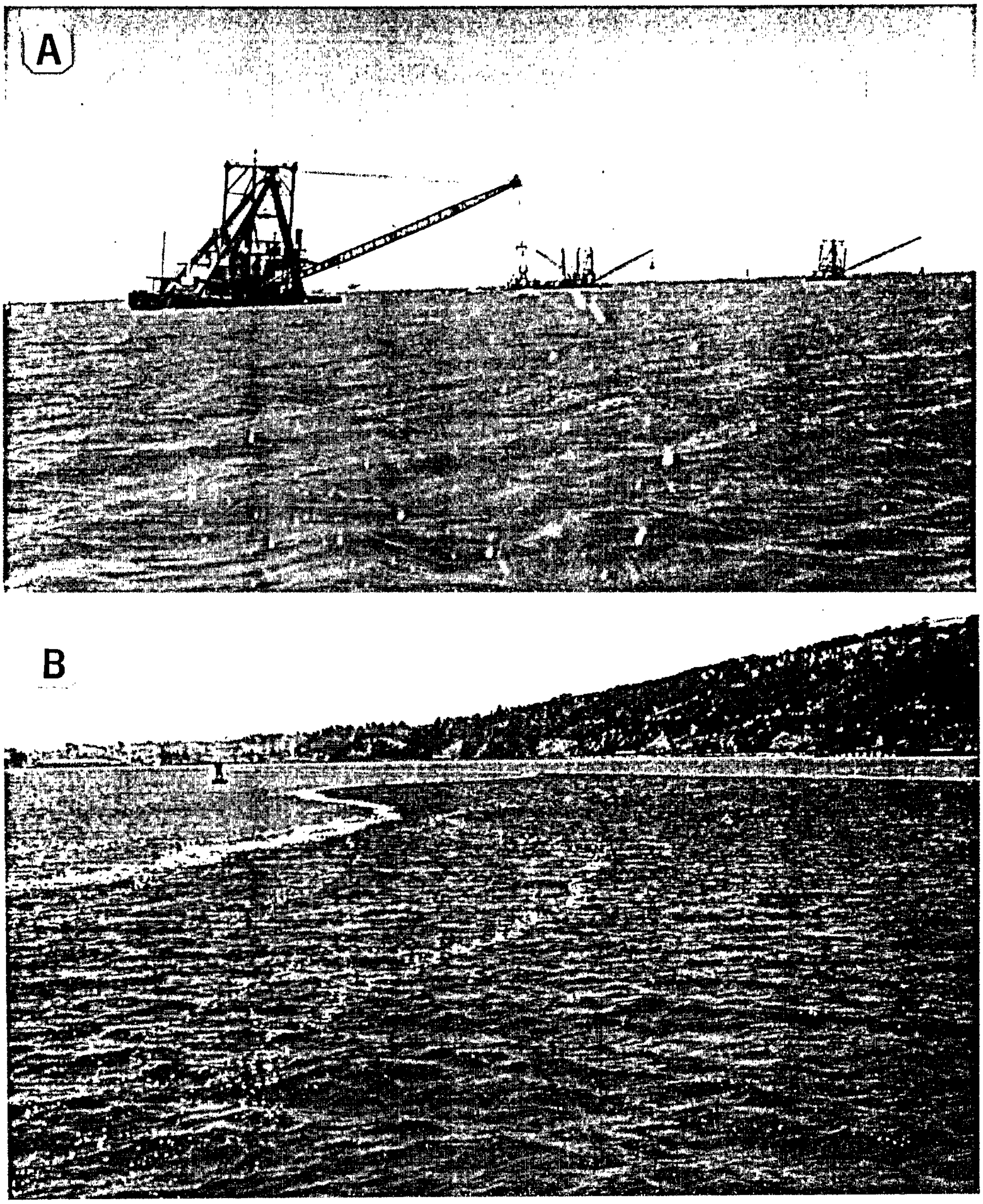

Figure 24. A, an example of sediment resuspension resulting from dredging in Honker Bay; B, an example of suspended sediments transported tidally near Martinez.

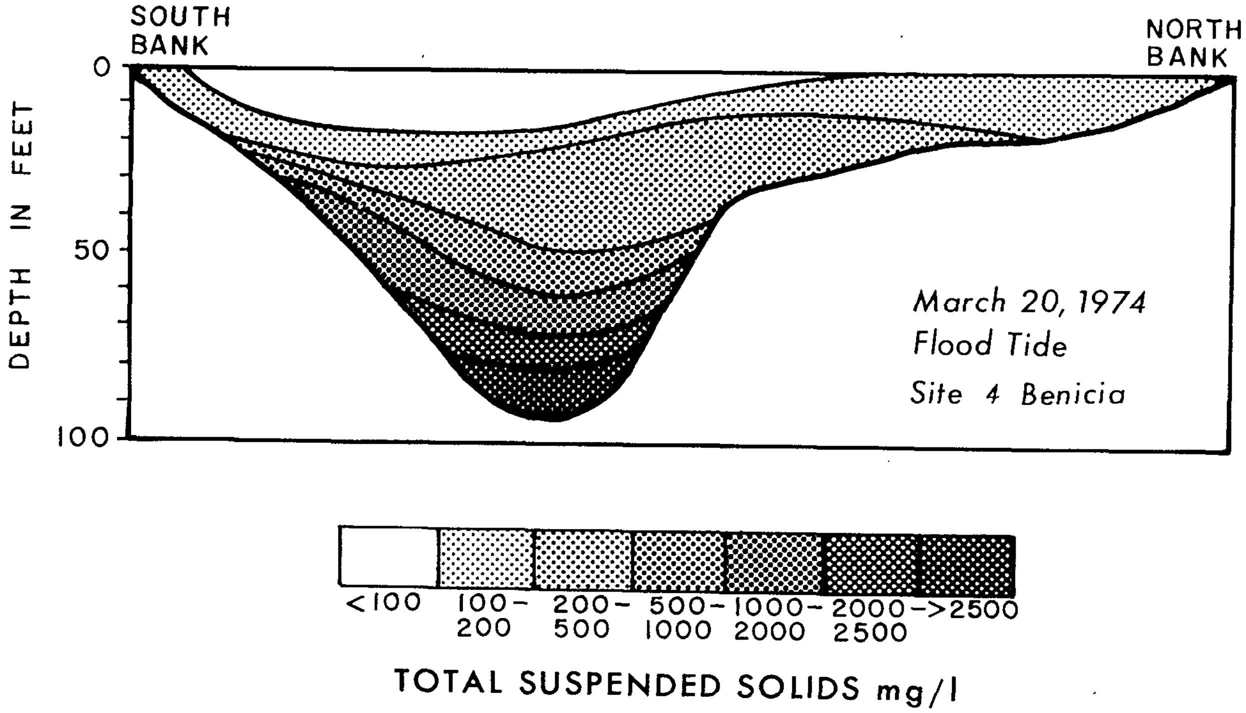

Figure 25. Distribution patterns of suspended solids across the channel at site 4 (Benicia) during maximum flood tide velocity on March 20, 1974.

> "Under slightly less-than-average river-inflow conditions, according to a computation made by Simmons (1955, p. 7), the flow of bottom water is predominantly landward near the mouth of Carquinez Strait . . . and predominantly seaward at its eastern end near Martinez. Because this places the nodal point of the bottom circulation in Carquinez Strait, one should expect sediments to accumulate there. Fine sediments do not accumulate in Carquinez Strait, however, apparently because the current velocities are too large. The sediments probably enter Mare Island Strait, which is the location of the most serious dredging problem in San Francisco Bay. About 2 million cubic meters, or about one-third of all the sediment dredged in the entire San Francisco Bay system, are removed every year to maintain adequate channels into and within the Mare Island Naval Ship Yard."

Studies by R. B. Krone (personal communication) on dredging by certain marina owners in shallow areas along Carquinez Strait having relative low velocities have demonstrated sediment deposition rates as high as 17 feet in less than a year.

An example of the effect of estuarine bathymetry on TSS and turbidity concentrations in the main channel occurs near the end of the breakwater where the Sacramento River enters San Pablo Bay. Quite often, highly turbid waters following periods of high winds were observed flowing out of the shallow northeastern area of San Pablo Bay into the channel near the end of floodtides. An example of this occurred on the May 30 and 31, 1974, sample runs (Figures 13 and 14). Such a combination of wind resuspension, tidal circulation and bathymetry can create temporary areas of high turbidity in areas other than in the entrapment zone.

The cross-sectional distribution of suspended materials was determined at various sites during the course of the study. Although some constituents were found to be quite uniform at some sites, there were large differences noted at other sites. The channel configuration appears to be a significant factor influencing the distribution of suspended materials.

NUTRIENTS

Total organic nitrogen and phosphorus consisted primarily of particulate nitrogen and phosphorous (Figures 26 and 27). As would be expected, the distribution patterns of these constituents were similar to the distribution of other suspended materials. Consequently, measurements of these two parameters were discontinued in 1974 as the time involved in their collection and analysis did not appear to be justified.

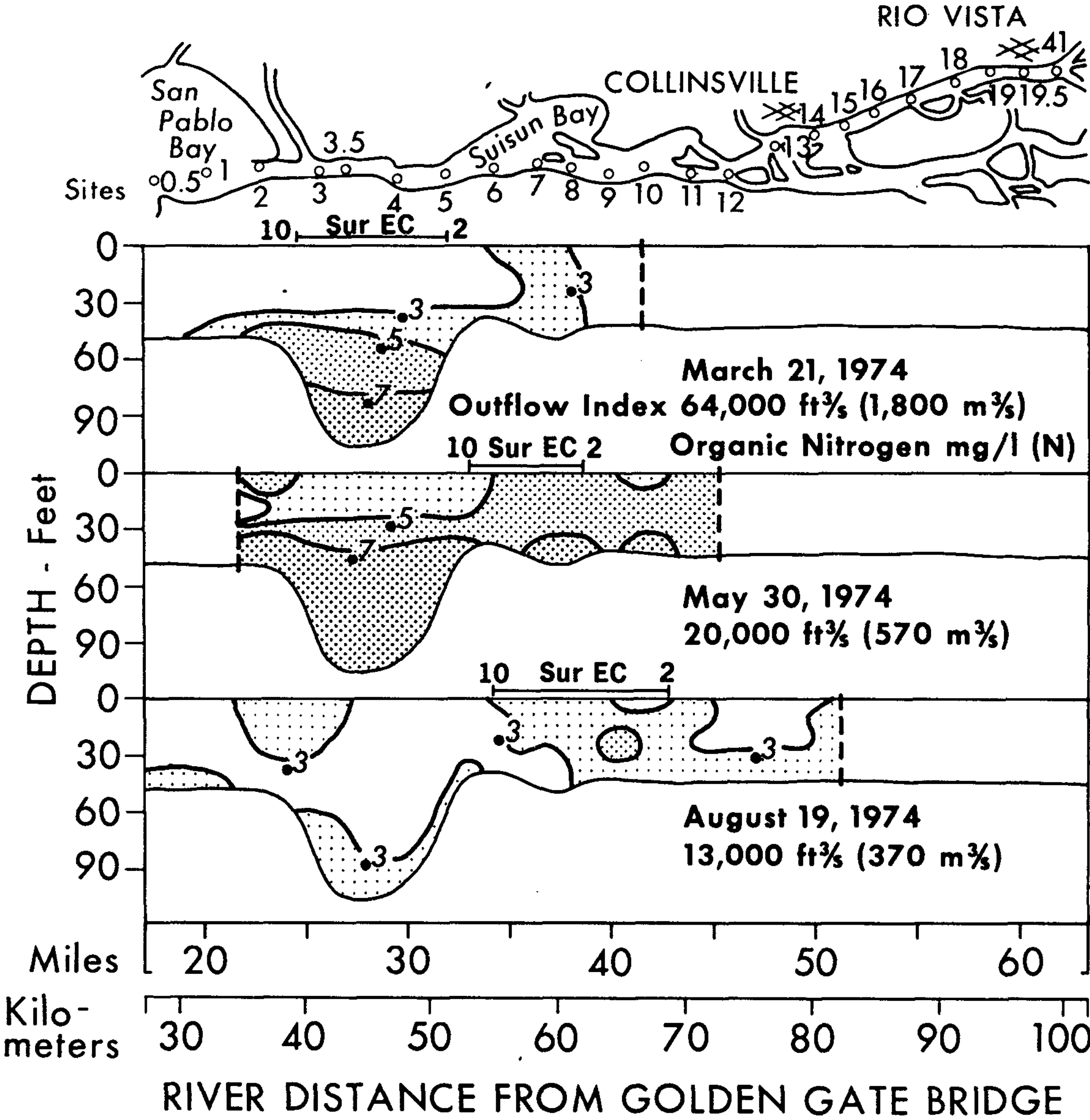

Figure 26. Total organic nitrogen distribution relative to salinity during high slack tides at various Delta outflows.

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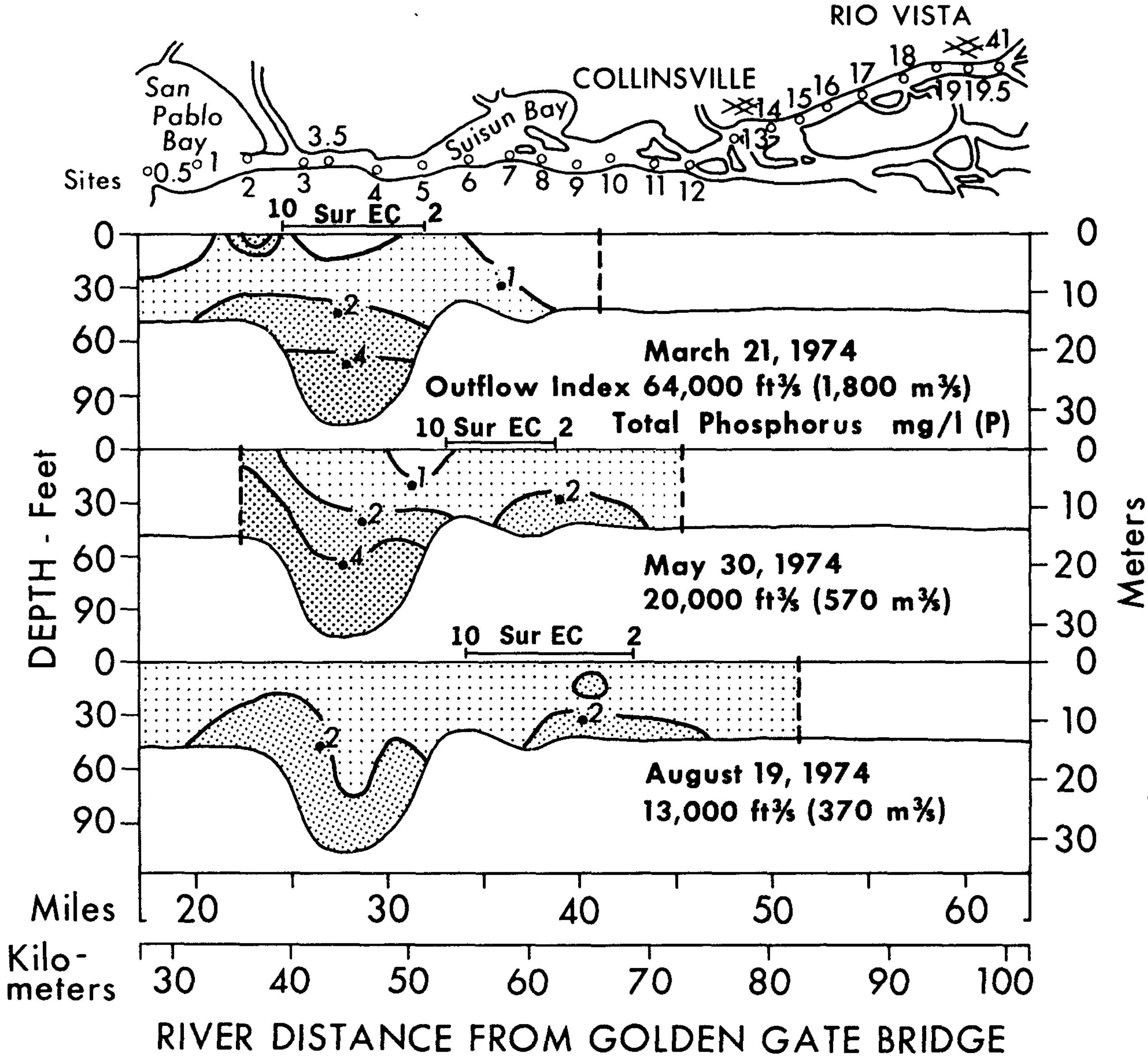

Figure 27. Total phosphorus distribution relative to salinity during high slack tides at various Delta outflows.

Dissolved constituents are not subject to entrapment by two-layered flow circulation. In general, the concentration of dissolved ortho-phosphate and inorganic nitrogen, (nitrate plus nitrite and ammonia) increased with depth and distance downstream in the study area (Figures 28-30).

In 1973-74 multidepth samples were evaluated. At times, reductions in the inorganic nitrogen forms occurred in areas of high algal growth in the entrapment zone and were attributed to assimilation by the phytoplankton. Routine monitoring has indicated periods in which nitrogen was depleted by the phytoplankton (Ball, 1977). Similar patterns have been observed in other estuaries (Mommaerts, 1969). Ortho-phosphate was never found to be at concentrations limiting phytoplankton growth.

In 1976 and 1977, only surface concentrations of dissolved nutrients were evaluated. Typically, the maximum concentration of the dissolved nitrogen and phosphorus forms occurred downstream of the entrapment zone. It was concluded the increases in concentration were the result of numerous municipal and industrial waste discharges in the area and were not directly associated with the entrapment zone.

Dissolved nitrogen and phosphorus were at relative high concentrations in both 1976-77 and were not limiting phytoplankton growth in the study area.

The typical seaward decrease in dissolved silica (Figure 31), measured throughout the study was attributed to dilution with low silica seawater. During periods of high algal growth in Suisun Bay (such as August 1970) dissolved silica was nearly depleted (USBR, 1972). Petersen, et al., (1975b) also found similar distribution patterns of dissolved silica.

PHYTOPLANKTON

Measurement of the chlorophyll concentration is a relatively rapid and accurate quantitative method of estimating the total phytoplankton standing crop. Factors for converting chlorophyll _a_ to total photoplankton carbon vary from about 25 to 100 and are dependent on the dominant organisms and their physiological state (Strickland and Parsons, 1968). Algal growth potential studies conducted by the USBR have indicated that diatoms (the dominant group of algae in the study area) require on the average about 7 parts of nitrogen to produce one 1 part of chlorophyll by weight (USBR, 1972).

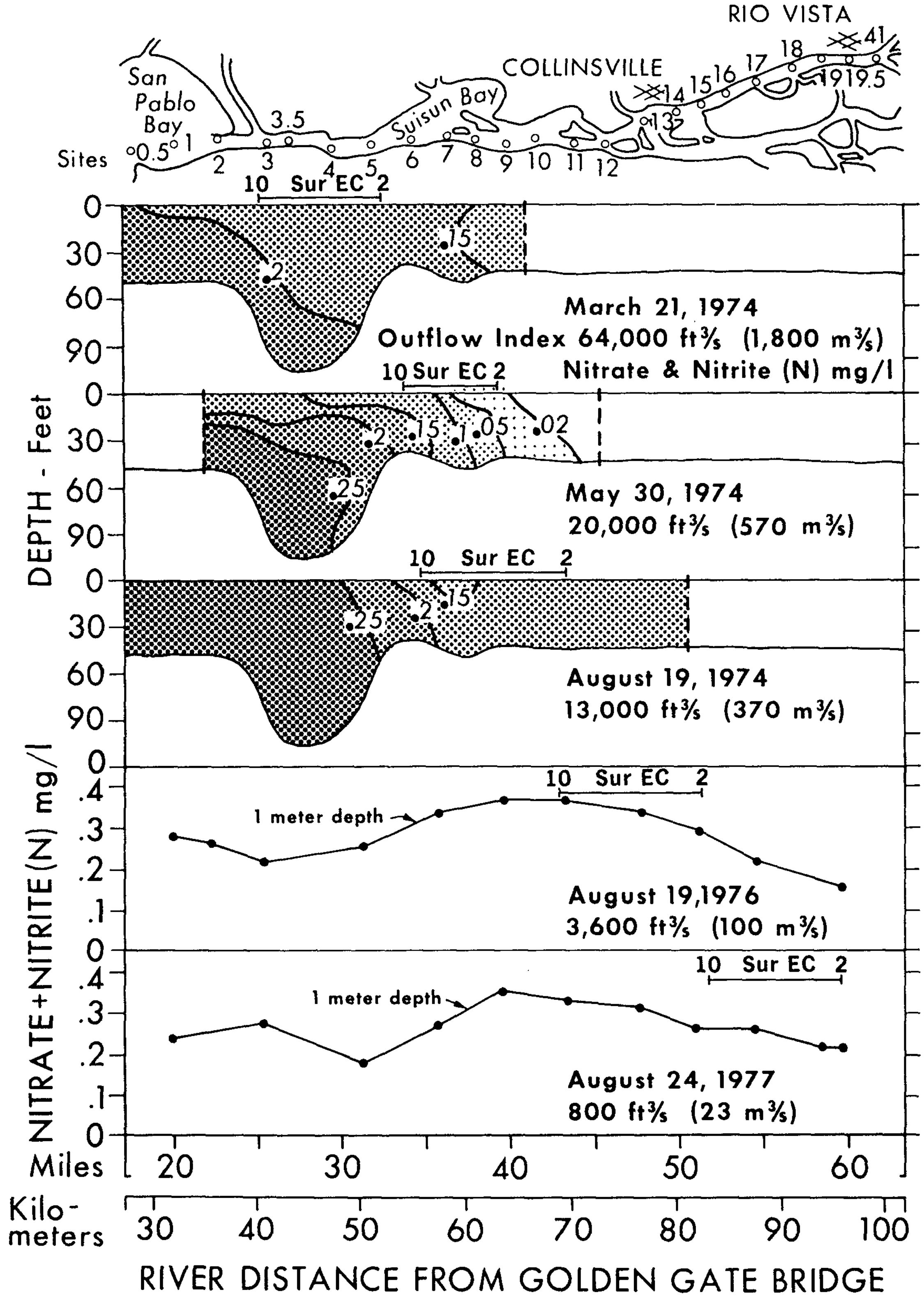

Figure 28. Nitrate plus nitrite distribution relative to salinity during high slack tides at various Delta outflows.

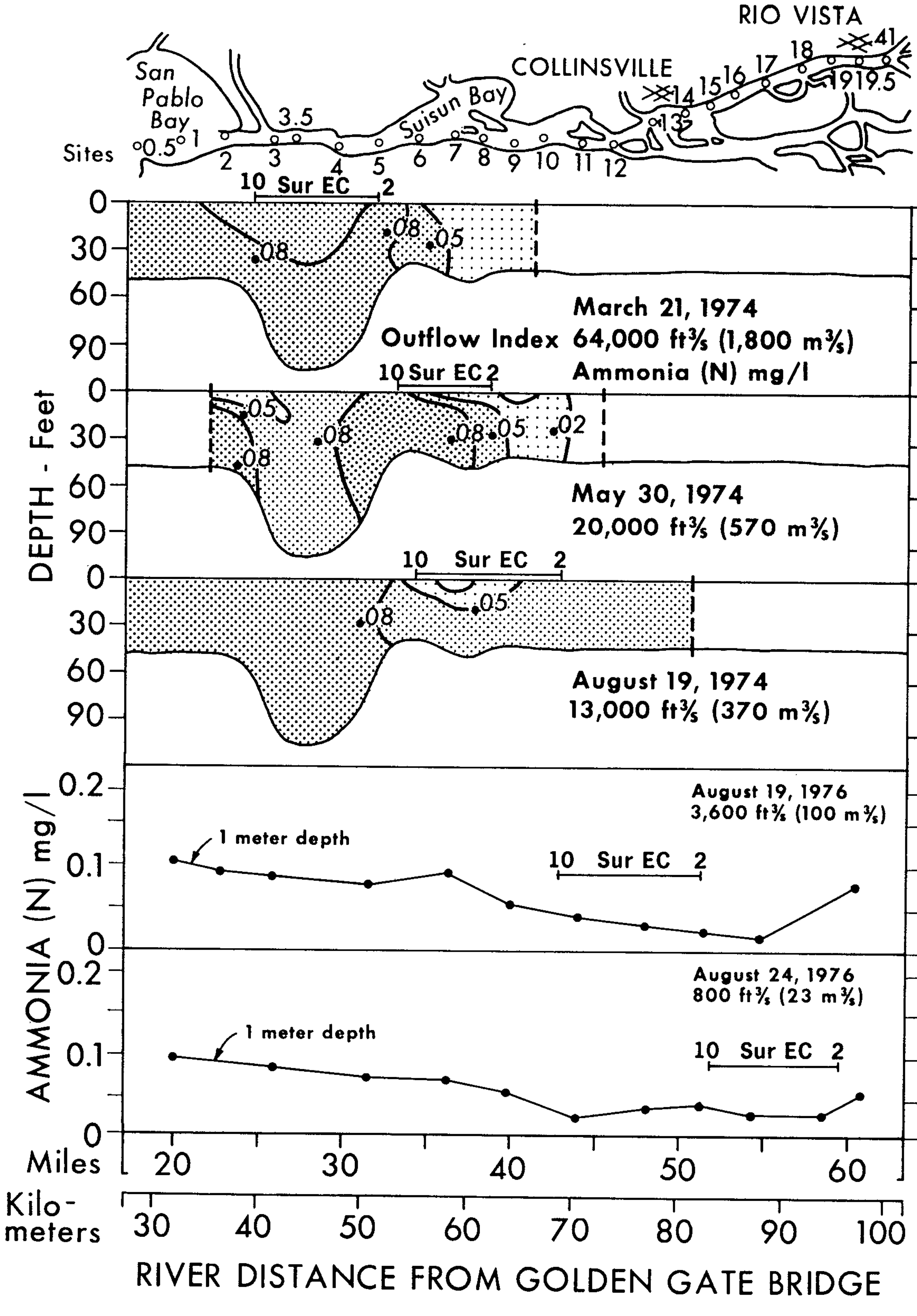

Figure 29. Ammonia distribution relative to salinity during high slack tides at various Delta outflows

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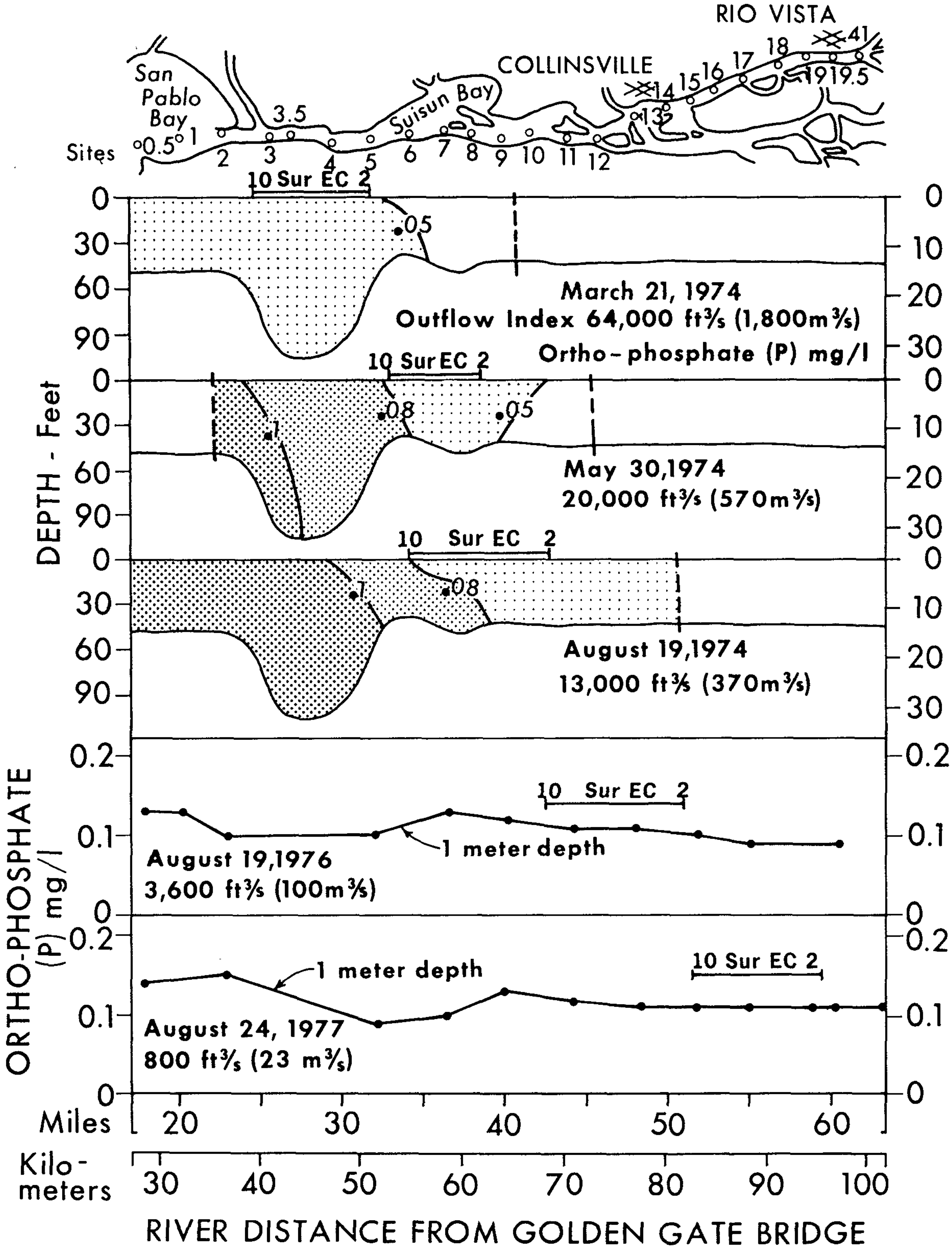

Figure 30. Ortho-phosphate distribution relative to salinity during high slack tides at various Delta outflows.

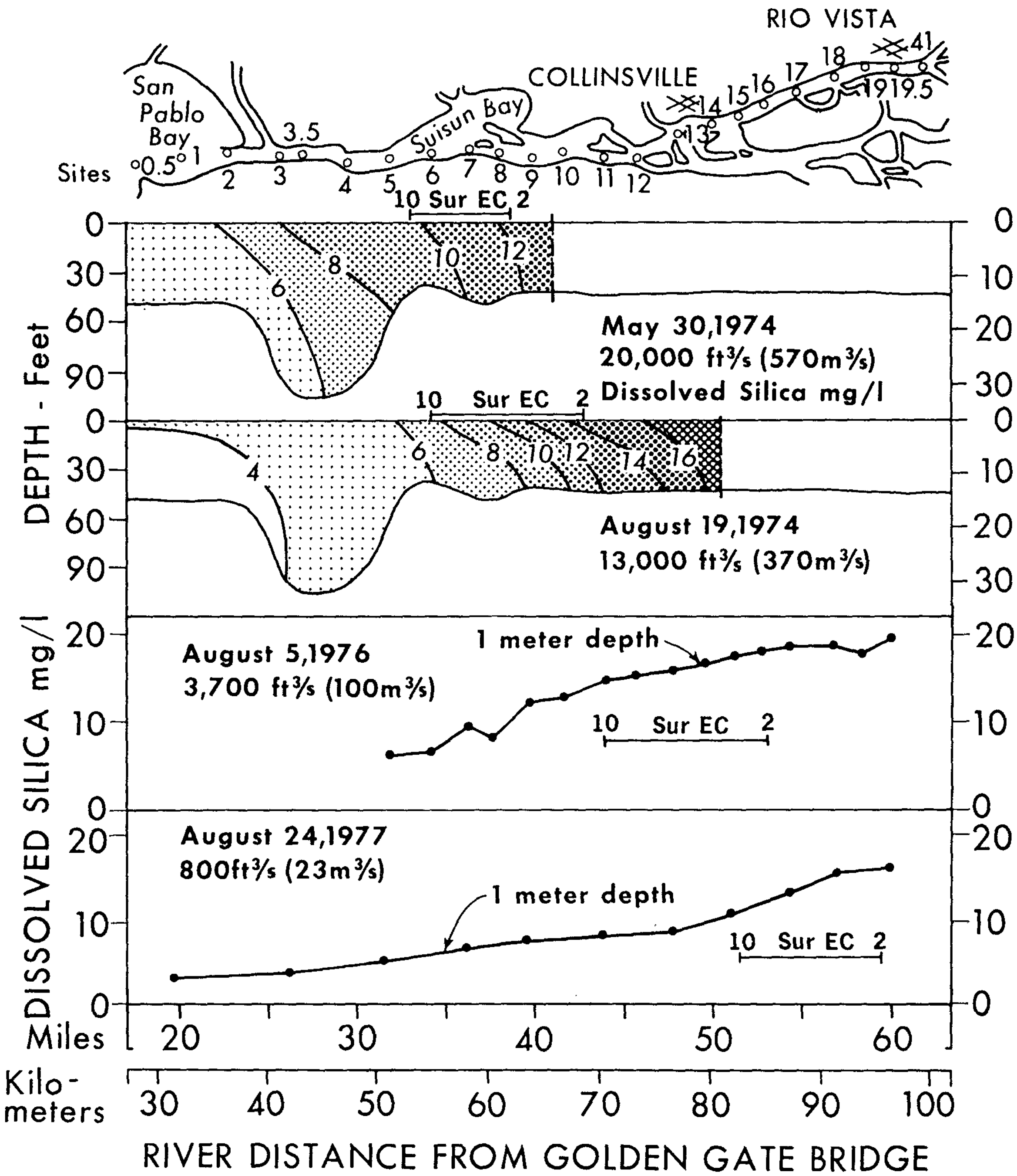

Figure 31. Dissolved silica (SiO_2) distribution relative to salinity during high slack tides at various Delta outflows.

Results and Discussion

Seasonal Phytoplankton Abundance

Phytoplankton abundance and the factors regulating their growth in the study area have been evaluated by Ball (1975 and 1977).

Phytoplankton blooms generally occur each year in both the Antioch-Emmaton-Jersey Point area (western Delta) and the Suisun Bay area (Figures 32a and b). The dominant organisms making up these blooms were always diatoms; however, the dominant genera varied between the two areas and between years.

In the western Delta, spring phytoplankton blooms occurred each year from 1969 through 1976 with maximum measured chlorophyll a concentrations of 25-50 ug/l depending on the year. Each year the timing of these spring blooms appeared to be related to increasing water transparency and decreasing Delta outflow. These two parameters were inversely related. Typically, chlorophyll a concentrations during the summer months were relatively low (5-20 ug/l) and to a limited extent were directly related to the water transparency. As opposed to the conditions in the spring, the average water transparency during the summer was directly related to the Delta outflow. This decreased summer water transparency occurred in part because lower outflow allowed greater upstream movement of the entrapment zone into the western Delta. In the western Delta during some years, the inorganic nitrogen concentrations were depleted to limiting levels at the peak of the spring blooms. Nitrogen depletion also occurred at times in the summer months during years such as 1969 and 1971 when both the water transparency and chlorophyll concentrations were high.

In the Suisun Bay area two peak phytoplankton bloom periods were detected each year between 1970 and 1975. The first bloom generally peaked in the spring around May with maximum measured chlorophyll a concentrations of about 30-40 ug/l. The blooms then declined in the early summer. This was typically followed by a summer bloom peaking around August with maximum values of about 40-100 ug/l, depending on the year. The timing of the first bloom each year appeared to be related to increasing water transparency and decreasing Delta outflow. In 1969 only a single bloom was observed and it occurred during the summer. In 1976 both a late winter and a spring bloom were observed, but no summer bloom occurred.

A phytoplankton bloom did not occur in Suisun Bay in 1977. In fact, chlorophyll levels during 1977 were the lowest on record. The low phytoplankton standing crop in the summer of 1976 and throughout the year in 1977 did not correspond to historical trends.

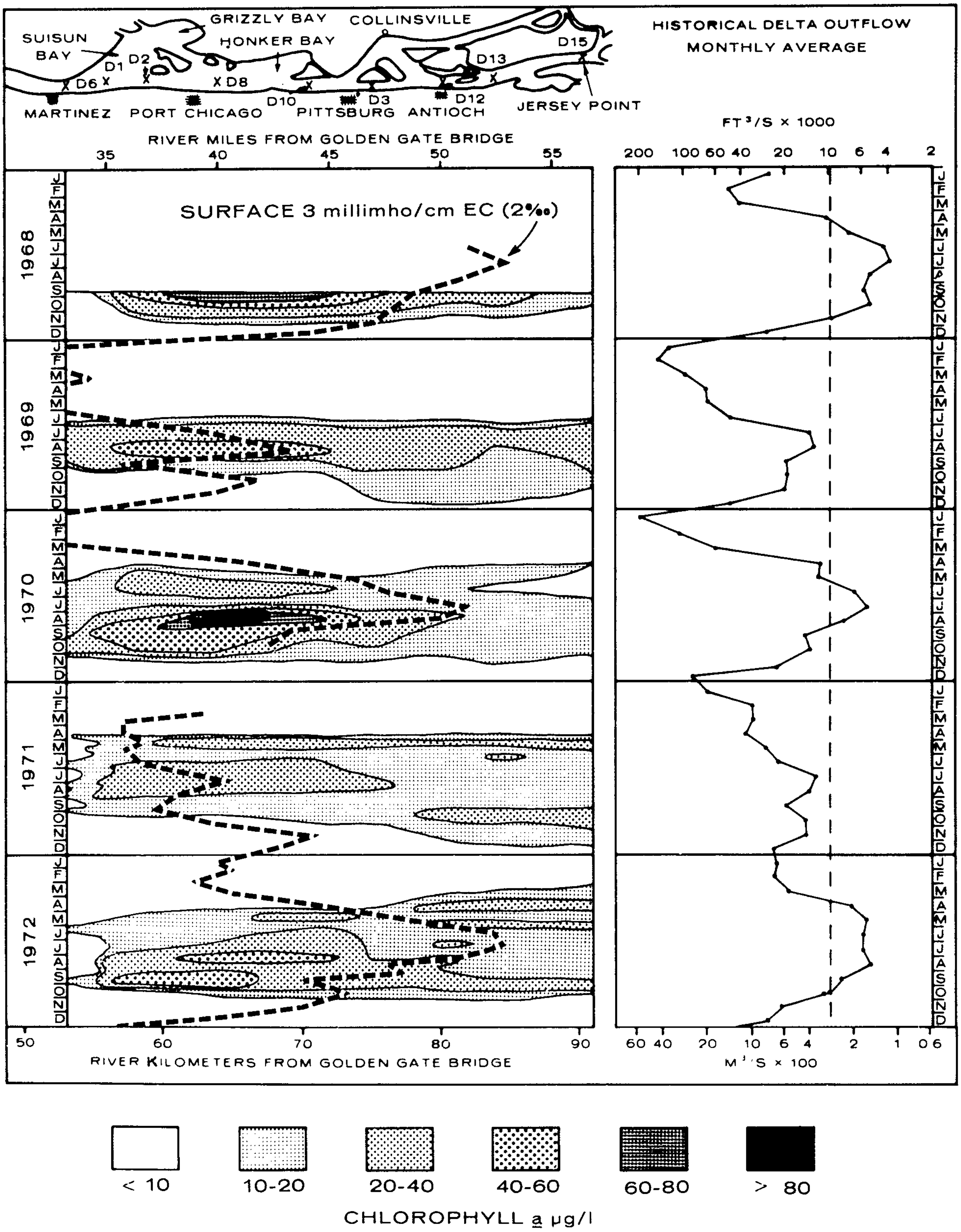

Figure 32a. Chlorophyll a distribution on high slack tides from 1968 – 1972, between Jersey Point and Martinez, as related to salinity intrusion and Delta outflow. (The 3 millimho/cm EC line is an approximate location of the upstream edge of the entrapment zone at high slack tides.)

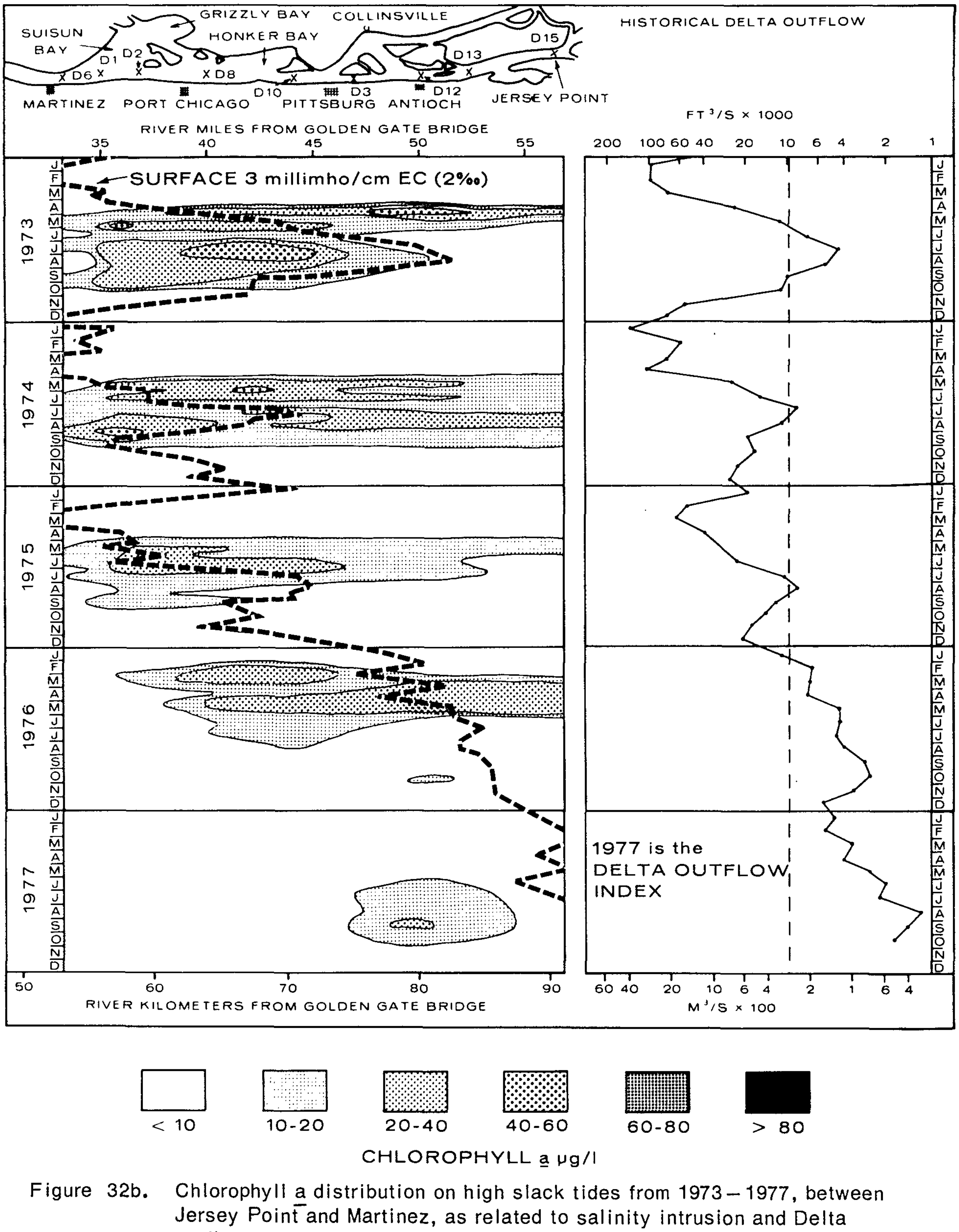

Figure 32b. Chlorophyll a distribution on high slack tides from 1973–1977, between Jersey Point and Martinez, as related to salinity intrusion and Delta outflow. (The 3 millimho/cm EC line is an approximate location of the upstream edge of the entrapment zone at high slack tides.)

Chlorophyll a and Phytoplankton Distribution

The same estuarine circulation forces thought to influence the accumulation of suspended solids and particulate nutrients in the entrapment zone also appear to determine the distribution of plankton. This was especially evident in the summer sample runs which were conducted following (1973) and during (1974) peak summer algal bloom periods (Figure 33). The maximum concentration of chlorophyll typically occurred in the same general location as the area of maximum TSS and turbidity (Figures 13 and 14).

During the 1973 and 1974 summer runs, the maximum chlorophyll concentration on the surface was about 3 miles downstream from the maximum concentration near the bottom. The same dominant genera of algae (Coscinodiscus, Skeletonema, and Cyclotella) were present, and each genus demonstrated the same general distribution pattern as chlorophyll a, Figures 34 and 35. The total numbers of the three genera varied; however, their relative distribution patterns were similar to the chlorophyll a. Generally, the maximum surface concentrations occurred approximately 3 miles downstream from the maximum bottom concentrations. These distribution patterns suggest at least a portion of the phytoplankton may be circulated upstream by two-layered flow.

During the August 1974 run, the surface chlorophyll a concentrations were only slightly lower than on the bottom. This difference may have been the result of different maximum chlorophyll a levels between 1973 and 1974 and/or differences in the timing of the sampling run relative to the bloom peak. The September 26, 1973, run was conducted about 1.5 months after the maximum level of the bloom had occurred. As a result, the algal concentration was declining and was only about one-half the maximum surface level that had occurred a few weeks earlier.

During the high outflow (March 1974) and medium outflow (May 1974) studies, relatively high chlorophyll concentrations for each run were found in the same general area as the maximum suspended solids. The highest concentrations, however, were found on the surface in San Pablo Bay at site 2 during the March 1974 run and upstream of Suisun Bay during the May 1974 run.

During the March 1974 run, a surface plume of turbid water was observed flowing from the northeastern shallow area of San Pablo Bay into the main river channel where samples were taken at site 2. The high chlorophyll concentrations at this site may also have originated in the shallows of San Pablo Bay. In theory, phytoplankton transported

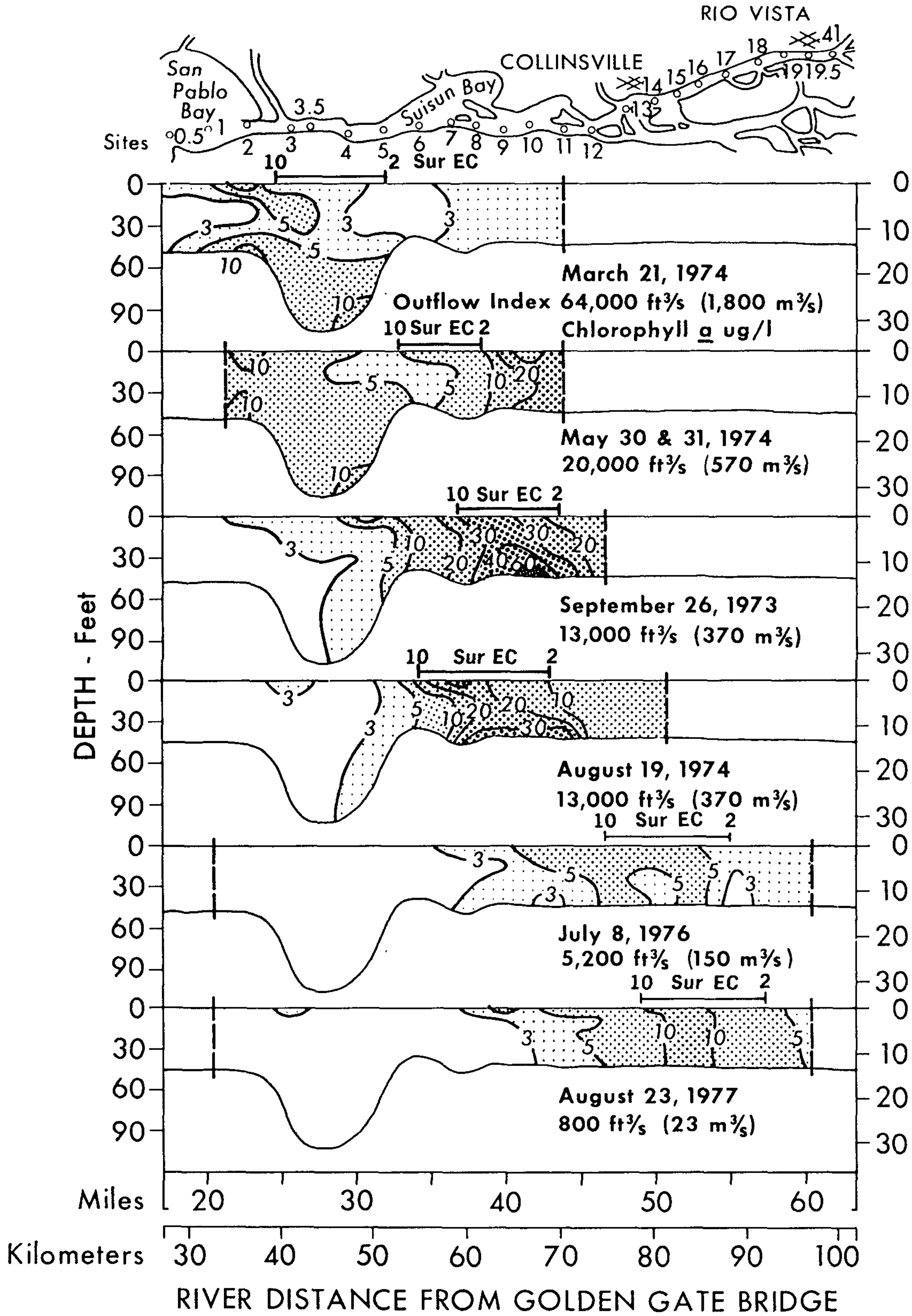

Figure 33. Distribution patterns of chlorophyll a relative to salinity during high slack tides at various Delta outflows.

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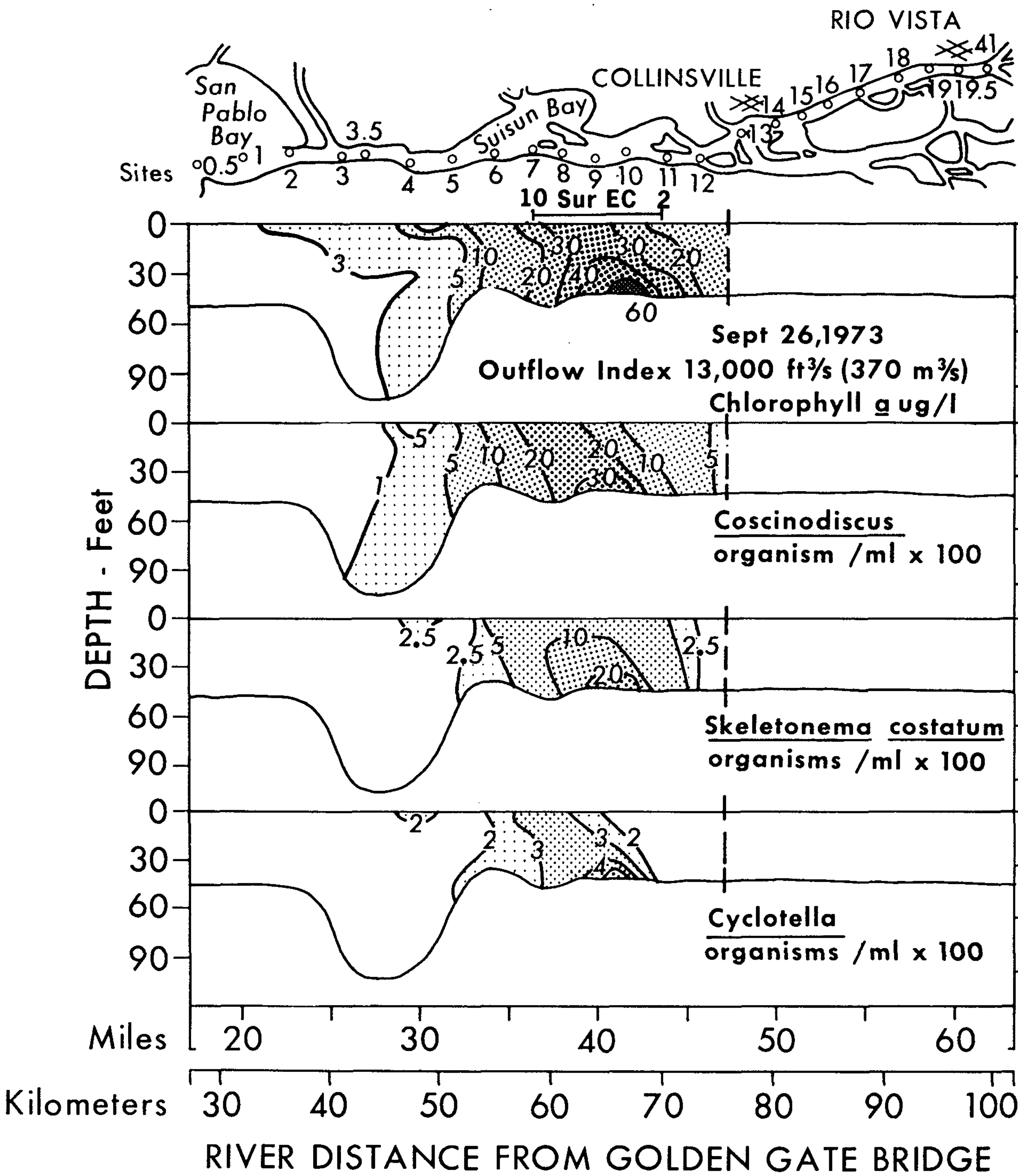

Figure 34. Distribution patterns of chlorophyll a and dominant phytoplankton genera relative to salinity during high slack tides on September 26, 1973. The peak of the summer phytoplankton bloom in Suisun Bay was measured 1½ months earlier in August.

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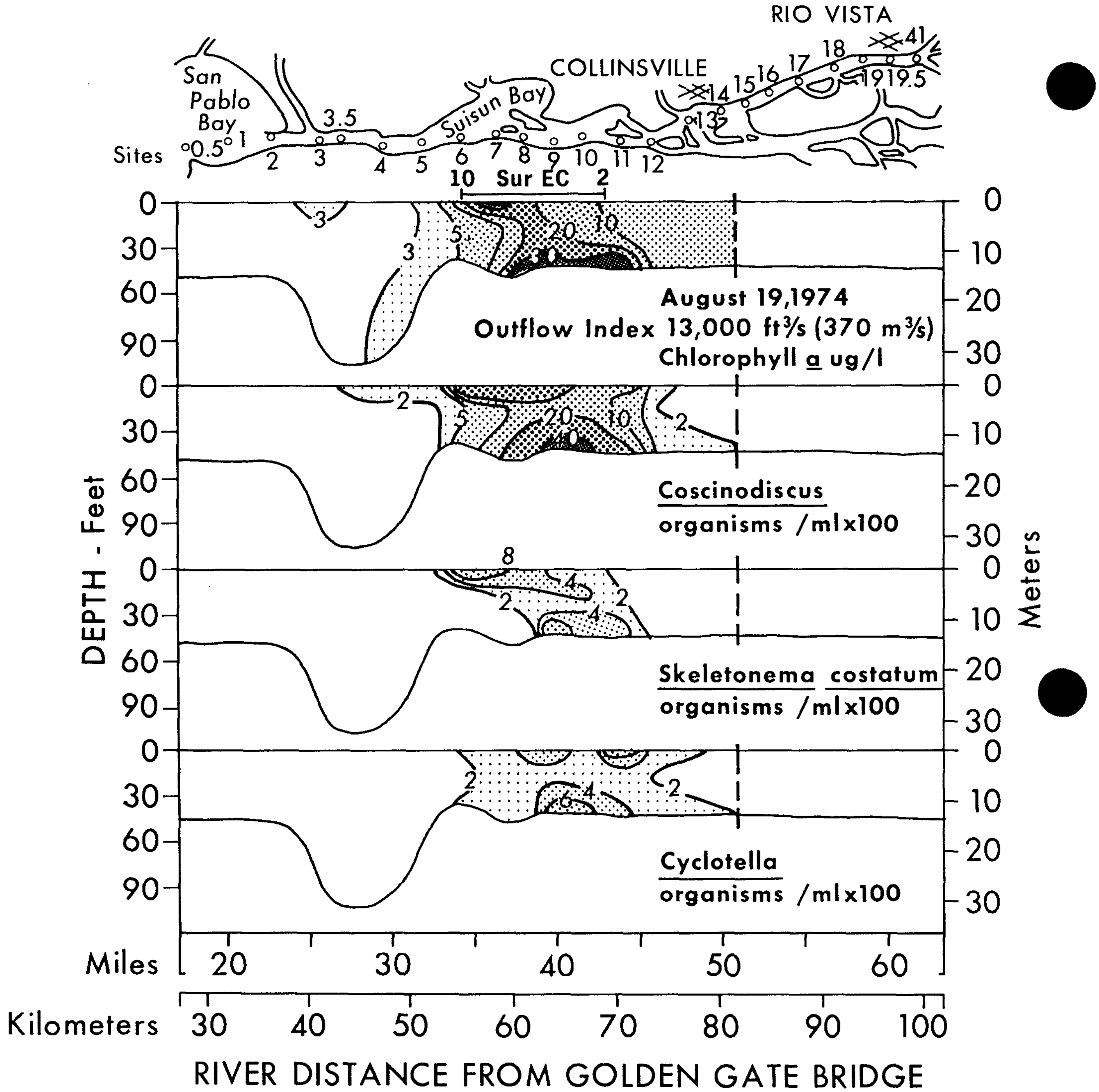

Figure 35. Distribution patterns of chlorophyll a and dominant phytoplankton genera relative to salinity during high slack tides on August 19, 1974, during the peak of the summer phytoplankton bloom in Suisun Bay.

from the shallows to the channel may settle into the lower layer and be transported upstream. Phytoplankton samples were not collected on this run.

The highest chlorophyll concentrations measured during the May 1974 run were thought to originate upstream of the Suisun Bay area. The phytoplankton data from the routine monitoring program indicate that one freshwater species, Skeletonema potamos (Weber), was in greatest abundance and was transported into the Suisun Bay area from the Antioch-Emmaton-Jersey Point area where a spring algal bloom was centered (Figure 36).

Another area of high algal concentration on May 30, 1974, was in the surface waters at site 2 in San Pablo Bay. The high concentration in this area may also have been due to the transport of algae from the shallow northeastern portion of San Pablo Bay, water from which flows out into the channel at site 2, during high slack tide. The dominant genera in this area were Cyclotella, Chaetoceros, and Skeletonema.

The other area of high chlorophyll a accumulation on May 30, 1974, was near the bottom in Carquinez Strait. No single genus or group of algae appears to have been responsible for this accumulation. The accumulation of chlorophyll in this area apparently was the result of various species of algae settling into the deeper water of Carquinez Strait and being concentrated along with the suspended sediments.

Coscinodiscus was another significant genus of phytoplankton found in the Suisun Bay area on May 30, 1974. This genus was primarily responsible for the spring algal bloom in the Suisun Bay area which occurred about 2 weeks prior to the sampling run. The distribution pattern of the Coscinodiscus population (Figure 36) resembles the chlorophyll a distribution on September 26, 1973, (Figure 33). The algal bloom in September 1973 was in a state of decline, as was the Coscinodiscus population on May 30, 1974.

On August 24, 1977, Coscinodiscus was also the dominant phytoplankton genus in the entrapment zone area (Figure 37). This run was made when near maximum chlorophyll concentrations were measured in 1977. Skeletonema costatum was greatly reduced in concentration from prior summer periods.

During the August 19, 20, and 21, 1974, runs, the maximum chlorophyll a concentration was higher in the channel during the maximum flood and low slack tides than during high slack tide (Figure 38). This may have resulted from tidal exchange between the more productive shallows with the channel water resulting in the

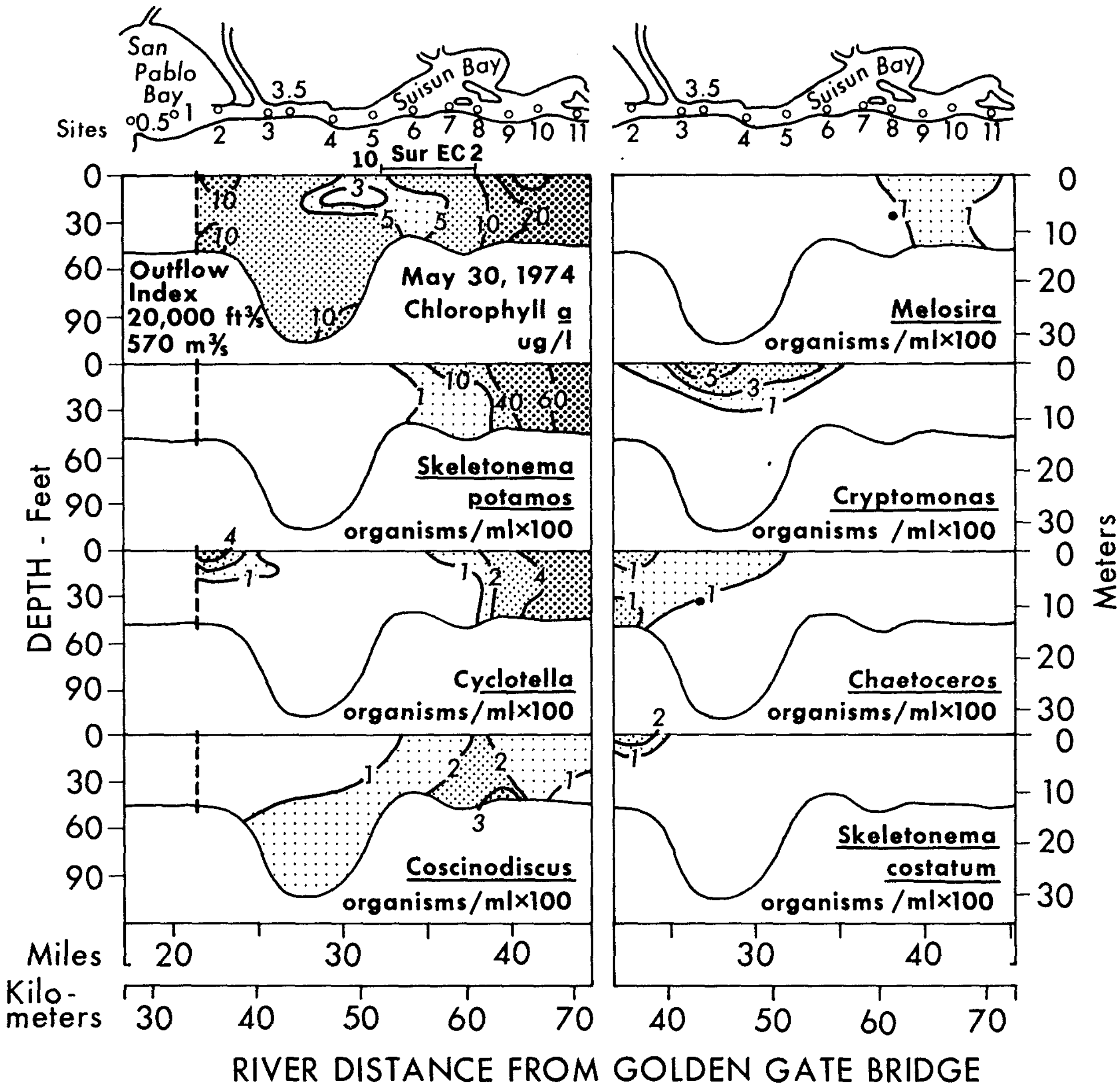

Figure 36. Distribution patterns of chlorophyll a and dominant phytoplankton genera relative to salinity during high slack tides on May 30, 1974. The peak of the spring phytoplankton bloom in Suisun Bay was measured about two weeks earlier.

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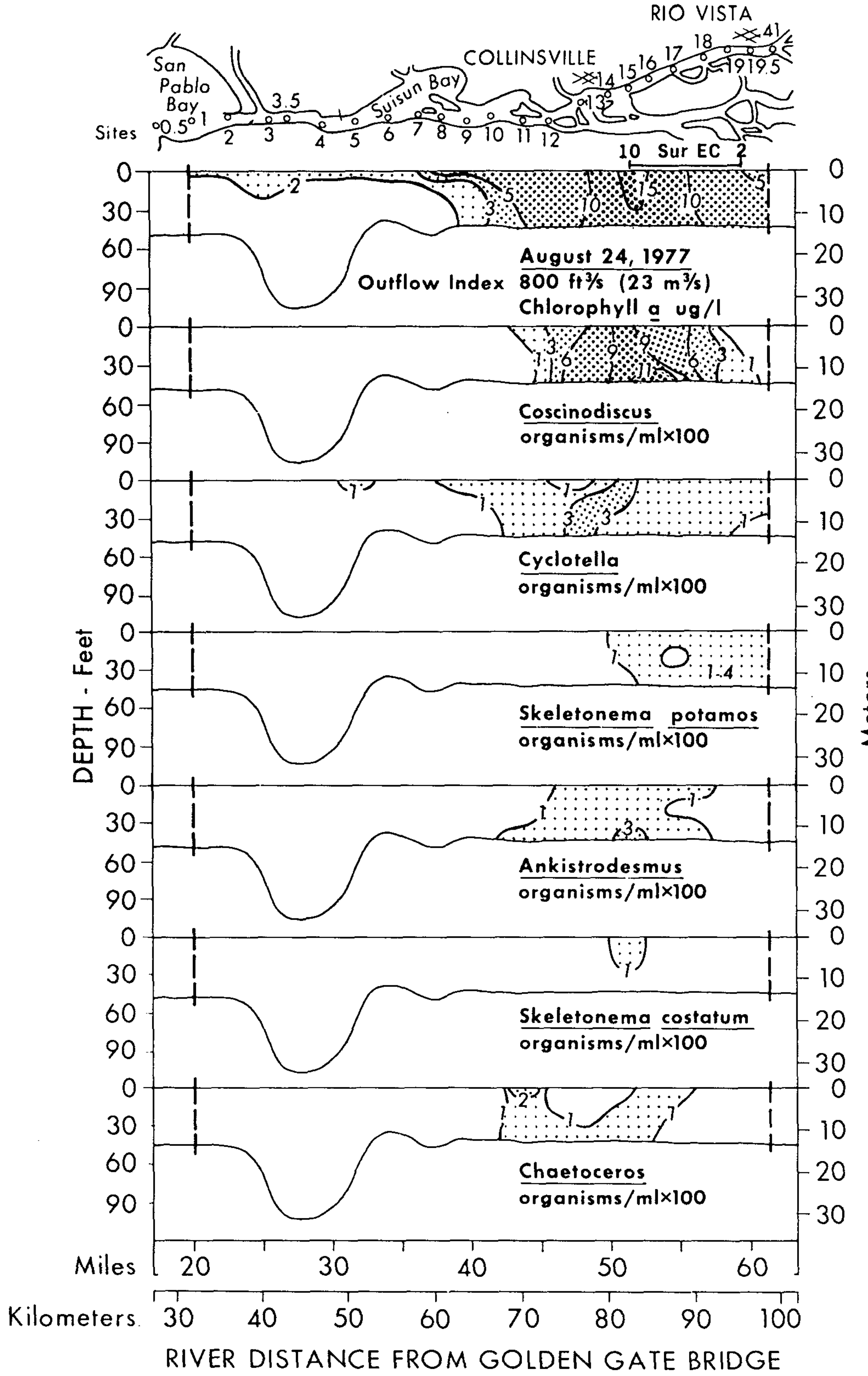

Figure 37. Distribution patterns of chlorophyll a and dominant phytoplankton genera relative to salinity during high slack tides on August 24, 1977, during peak phytoplankton abundance for the year.

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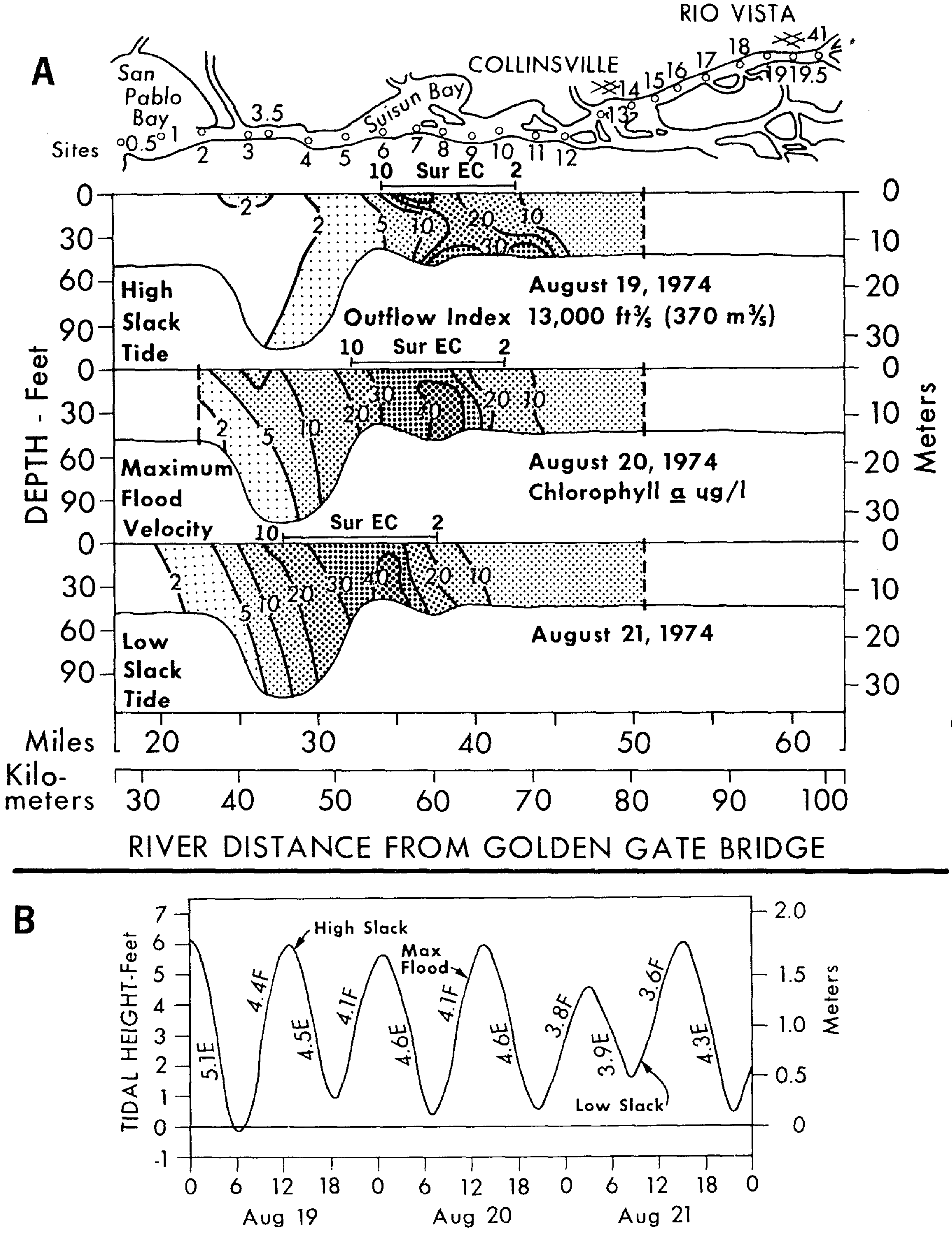

Figure 38. A, distribution patterns of chlorophyll a relative to salinity measured on three consecutive days during different tidal phases in August 1974; B, calculated Golden Gate Bridge tidal heights and maximum flood and ebb (F and E) velocities in knots.

sampling of different water masses. Also, resuspension of denser phytoplankton and/or detrital materials containing chlorophyll a may have occurred at higher tidal velocities. In 1977 when the entrapment zone was several miles upstream and more confined to channels, little difference in concentration was measured between tidal phases (Figure 39).

Pheo-Pigment Distribution

Some of the initial breakdown products of chlorophyll a which can be measured easily are the pheo-pigments. The concentration of pheo-pigments relative to chlorophyll a increases as the phytoplankton community experience various types of stress such as a few days without light, depletion of nutrients, zooplankton grazing, etc. The term percent chlorophyll a (of the total chlorophyll a plus pheo-pigments) is commonly used as an indication of the general physiological state of the algal community since it indicates the percentage of degradation products present.

The highest percent chlorophyll a occurred during the periods of high phytoplankton standing crops such as in 1974, while the lowest percents occurred during periods of lowest crops in 1977 and during the 1974 winter run (Figure 40). It was also evident that in the areas upstream of the entrapment zone less top to bottom variations occurred, while downstream of the zone the bottom concentration was as much as 40 percent lower than the surface concentration. The consistently low percent chlorophyll a (less than 30 percent) with increasing depth in Carquinez Strait suggests the algae were in a poor physiological state, there were accumulations of detrital plant material, the phytoplankton were under light stress, there was heavy zooplankton grazing, and/or there was reduced vertical mixing of the water column.

Yentsch (1965b) demonstrated the percent chlorophyll a began to decrease when algal cultures were maintained in total darkness for periods of time greater than 70 hours. Yentsch (1965a) also stated grazing zooplankton may ingest a considerable amount of chlorophyllous material and presumably the acidity of the gut could transform this material to pheo-pigments which would be eliminated in fecal pellets.

The highest percent chlorophyll a occurred during the high slack tide as compared to lower percents on the low slack tide and lowest percent on the maximum floodtide (Figure 41). The reduction in the percent chlorophyll a during the floodtide indicates there was an increase in the percent pheo-pigments. There was also an increase in both chlorophyll a and pheo-pigment concentration. This increase suggests during higher tidal velocities resuspension of larger or more dense detrital chlorophyllous materials and/or fecal pellets (often containing relatively high pheo-pigment levels)

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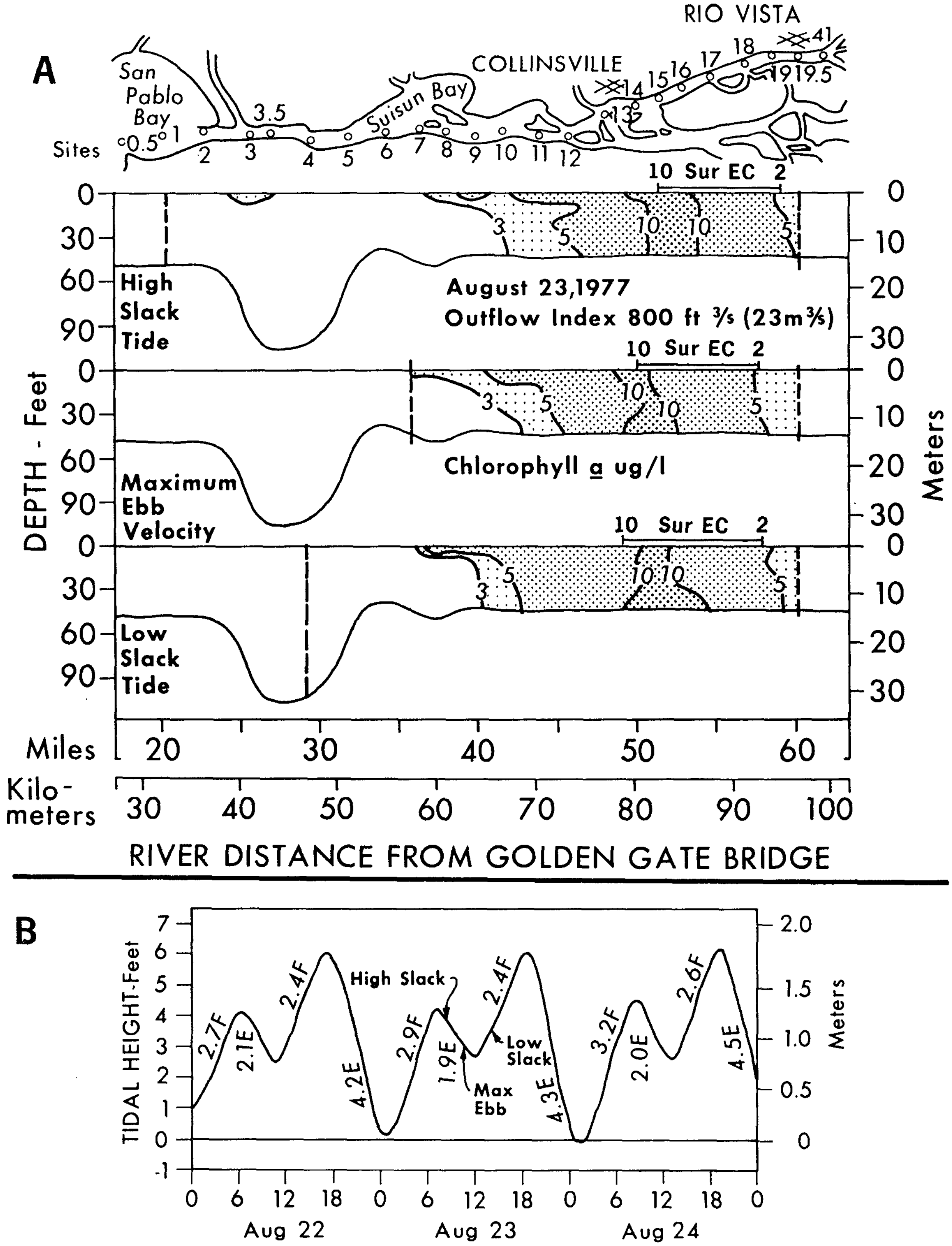

Figure 39. A, distribution patterns of chlorophyll a relative to salinity measured during three consecutive tidal phases on August 23, 1977;
B, calculated Golden Gate Bridge tidal heights and maximum flood and ebb (F and E) velocities in knots.

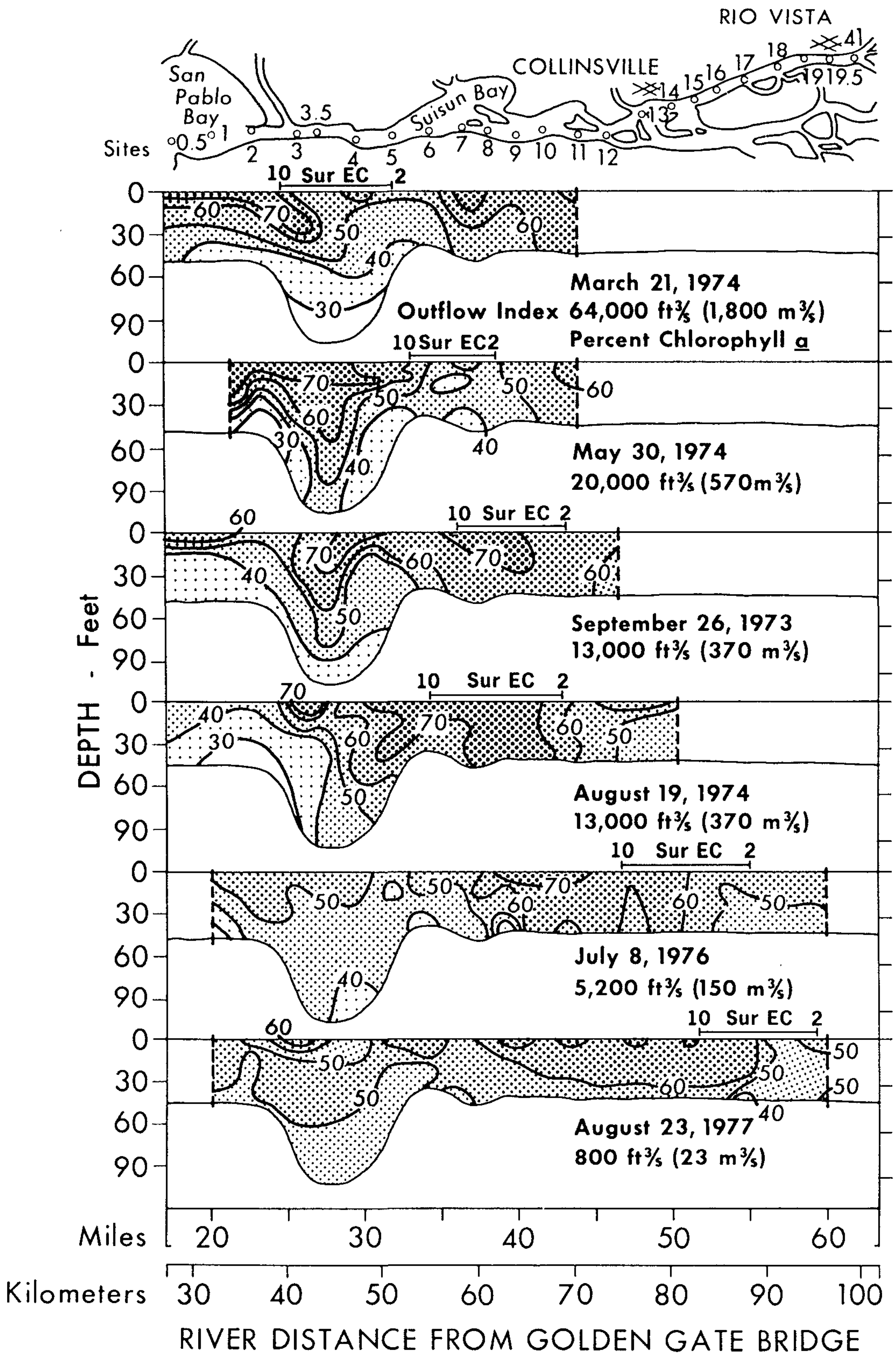

Figure 40. Distribution patterns of percent chlorophyll a relative to salinity on high slack tides at various Delta outflows.

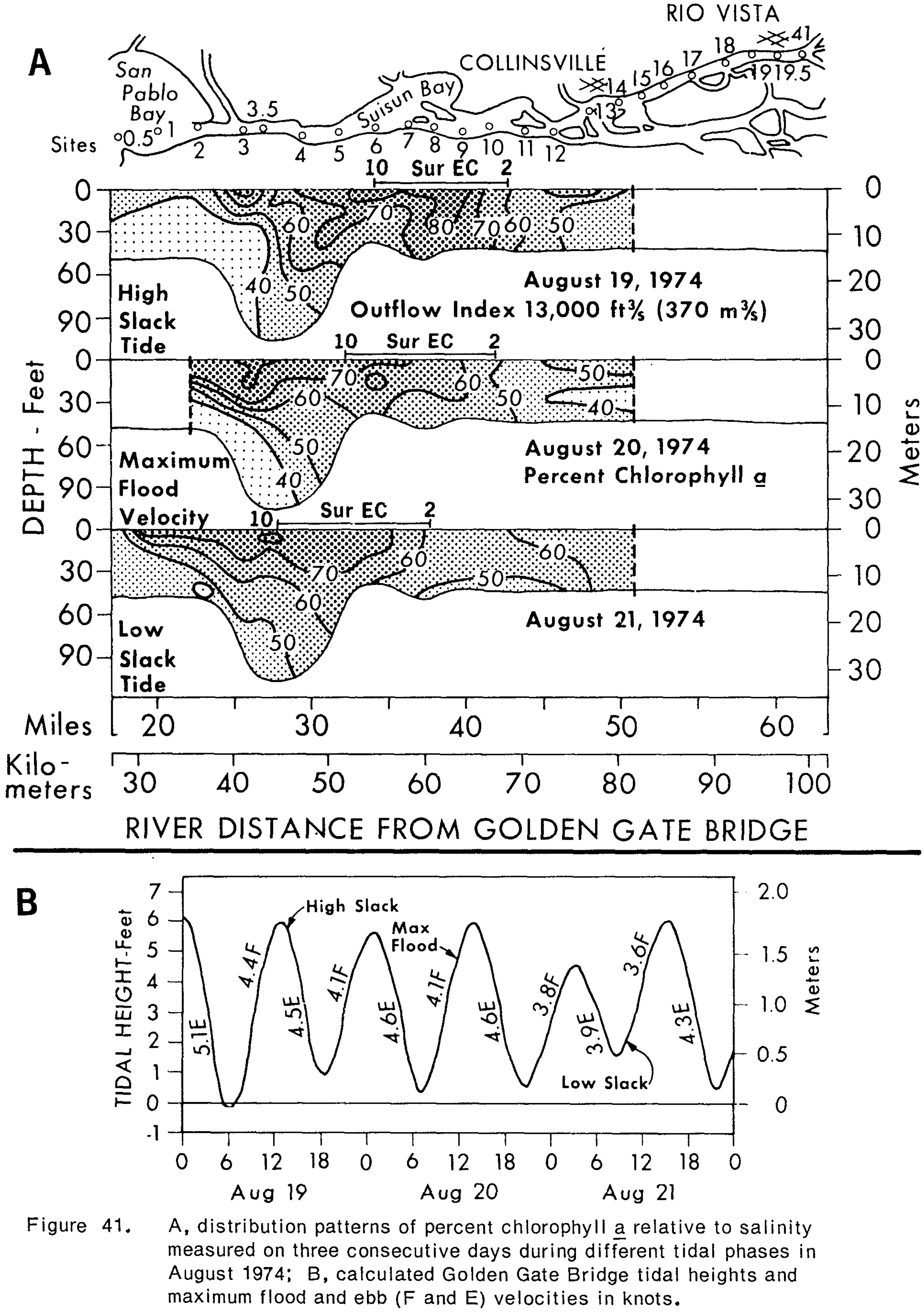

Figure 41. A, distribution patterns of percent chlorophyll a relative to salinity measured on three consecutive days during different tidal phases in August 1974; B, calculated Golden Gate Bridge tidal heights and maximum flood and ebb (F and E) velocities in knots.

occurred. Nichols and Poor (1967) found in the Rappanhannock Estuary the concentration of fecal pellets increased during higher tidal velocities.

The Entrapment Zone Location - A Factor Influencing Phytoplankton Abundance

Apparently there are several factors interacting to influence maximum phytoplankton concentrations. The location of the entrapment zone adjacent to the Honker Bay area is one factor which appears to greatly stimulate phytoplankton growth in the entire Susiun Bay area.

The unusually low phytoplankton standing crop in Suisun Bay during the summer of 1976 and throughout 1977 was contrary to predictions based on historical trends. Typically, before 1976 (1968-75 data period) the standing crop tended to be highest in years with the greatest water transparency. A number of field and laboratory studies were conducted during 1977 to evaluate the low phytoplankton standing crop associated with low outflow conditions. The factors evaluated included: water transparency, water temperature, solar radiation, salinity, nutrient limitation, toxicity, parasitism, zooplankton grazing, benthic filter feeding, and the location of the entrapment zone.

Evaluation of 1976 and 1977 data indicated water transparencies in Suisun Bay were approximately double (Figure 16) those of the previous years of high standing crop (Figure 32a and b), while solar radiation, water temperatures, and algal macro-nutrients were within the normal range. Furthermore, the phytoplankton standing crop in the northern and southern Delta during 1976 and 1977 were the highest recorded although climatical conditions in these areas were similar to Suisun Bay.

A number of algal growth potential (AGP) and phytoplankton productivity studies (light and dark bottle DO method) were conducted during 1977 to determine if nutrient depletion, increased salinity, or toxicity might have been responsible for the low phytoplankton standing crop. Results of these studies were compared to similar studies conducted during years of relatively high phytoplankton standing crops (1970-1974).

Results of the AGP tests (present and past studies) demonstrated the growth rate of the endemic phytoplankton tend to increase with increasing salinity suggesting to us salinity intrusion into Suisun Bay during the low flow years did not directly inhibit the algal growth rates. Furthermore, because concentration of phytoplankton in unaltered water of the AGP tests peaked several times higher than in the field, it appears that neither toxicity nor low concentrations of macro- or micro-nutrients were limiting algal growth. The primary productivity test results in 1977 also supported this contention as the dissolved oxygen production per unit chlorophyll was equal to or higher than that of previous years.

Although algal succession from Skeletonema costatum to Chaectoceros sp. (which possibly could have resulted from parasitism) occurred in a few flasks in the AGP tests, actual parasites were not observed.

Evaluation of zooplankton data (collected by the DFG) demonstrated zooplankton concentrations were lower than normal, suggesting grazing rates on phytoplankton should also have been lower than normal.

Benthic sampling in Suisun Bay by the DWR and USBR in 1976 and 1977 indicated there may have been some movement of marine benthic organisms into Suisun Bay. However, because there is little previous data available from that area with which to compare, it was impossible to draw any definite conclusions. Comparison of 1976 and 1977 data with future years of high phytoplankton standing crops may provide some insight into the possible significance of benthic filter feeding on the phytoplankton standing crop.

The long-term data (Figure 32a and b) indicated moderate to high chlorophyll a concentrations (above 20 ug/l) were observed when Delta outflows were approximately in the 4,000 ft^3/s (110 m^3/s) to 25,000 ft^3/s (700 m^3/s) range. When the outflows were below 4,000 ft^3/s (110 m^3/s), the phytoplankton standing crop either declined or remained low. The above flow range places the tidally averaged location of the entrapment zone at various positions adjacent to the Suisun-Honker Bay area. The highest chlorophyll concentrations were measured when the outflow was in the 5,000-7,000 ft^3/s (140-200 m^3/s) range as in August of 1970, 1972, and 1973, and September of 1968. This outflow range places the average tidal location of the entrapment zone (based on 2-10 millimho/cm EC range) adjacent to upper Honker Bay.

The winter phytoplankton bloom in early 1976 may have been influenced by the location of the entrapment zone (Figure 32b). Winter outflow was low that year and the entrapment zone was located adjacent to the Suisun-Honker Bay area in February - much earlier than normal. A substantial algal bloom developed which was the earliest recorded for this area. Significantly, during the bloom water temperatures were only about 12 C and the photoperiod was short (however, water transpariences were high). This bloom declined in March as the water transparency decreased. A second bloom developed in April. The second bloom declined as the entrapment zone moved upstream in June 1976.

When the entrapment zone was upstream of Honker Bay during low Delta outflows (generally less than 4,000 ft^3/s or 110 m^3/s), such as occurred in July and August of 1966 (DFG data), July 1970, June-December 1976, chlorophyll concentrations either remained low or were declining. As the 1976 drought continued into 1977 and Delta outflows remained low, the entrapment zone remained several miles upstream of Honker Bay for the entire year. Significantly, 1977 was the first year on record a phytoplankton bloom did not develop in Suisun Bay. The chlorophyll a concentration in Suisun Bay was generally less than 5 ug/l with an occasional value of about 10 ug/l.

During 1977 the highest chlorophyll a concentrations (nearly 20 ug/l) in the western Delta-Suisun Bay area were measured in the entrapment zone (2-10 millimho/cm EC water) at locations above Collinsville on the Sacramento River and above Antioch on the San Joaquin River. Chlorophyll a concentrations during 1977 for these sites were consistent with the last few years (1969-75, however, the entrapment zone was farther downstream). Water transparencies at these sites in 1977 were lower than normal, suggesting the higher standing phytoplankton crop was maintained by the entrapment zone.

An important factor in evaluating algal growth is the algal residence time. The growth rate is proportional to the length of time algal cells reside in light. The residence time in any given stretch of a river can be easily estimated by knowing the volume of water and rate of flow. However, in an estuary where two-layered flow and tidal exchange occur, the residence time of suspended materials (including algae) can either be greatly increased or reduced over that of the net downstream flow of water. The residence time of phytoplankton in two-layered flow circulation has not been directly measured. In theory, phytoplankton tend to be carried seaward if their settling rate is less than the net vertical velocity; tend to be recirculated to and about the entrapment zone if their settling velocity is nearly equal to the net vertical velocity; or become entrapped and remain near the bottom if their settling velocity is much greater than the net vertical velocity.

Certain algal species of the genus Coscinodiscus are consistently associated with the entrapment zone (Figures 34-37). These organisms have thick cell walls, generally have inorganic particles attached to their exterior, and rapidly settle in counting chambers. Their settling velocity relative to the net vertical velocity may provide these organisms with an ecological advantage which allows accumulation in the entrapment zone. In contrast certain species of the genus Chaetoceros have cells much smaller in size which settle very slowly, have high growth rates, and at times become very dominant in the AGP test. Chaetoceros probably did not become dominant in the entrapment zone because their settling rates were so low; however, they often were the dominant form downstream of the entrapment zone.

The examination of settling rates of algae and how flocculation influences their settling and entrapment is a proposed direction of study of the four agencies.

A substantial phytoplankton bloom in the summer of 1977 with maximum chlorophyll a concentrations near the water's surface of over 700 ug/l occurred in the McAvoy marina located on the south side of Honker Bay. This was caused almost entirely by motile organisms of the dinoflagellate genus Exuviella. The intensity of the bloom gave the water a reddish brown cast. This same organism was observed in Suisun Bay in 1977 at very low concentrations. Apparently, such areas, although physically connected to the main channel, are hydraulically isolated from the effects of wind, tidal mixing and river flushing. The most logical explanation seems to be the residence time of the algae are longer in these isolated areas than in the main channel and their mobility can maintain them near the surface.

Exactly how reduced outflow and the location of the entrapment zone influenced the phytoplankton standing crop in the Suisun Bay area is uncertain. There are, however, several hypotheses which considered either singularly or in some combination might explain how the upstream movement of the zone could have caused a reduction in the Suisun Bay phytoplankton standing crop during the summer of 1976 and throughout 1977.

1. Decreased phytoplankton residence time in the Suisun Bay area when the entrapment zone was located upstream. In rivers, the residence time of suspended materials increases as riverflow decreases. The record high phytoplankton crop in 1976 and 1977 in the northern and southern Delta (upstream of the study area) is believed to be attributed to the increase in phytoplankton residence time resulting from lower riverflows.

However, in the fresh-saltwater mixing zone of the estuary, the hydraulics are much more complex. In this area, the longer residence time in the entrapment zone, relative to the immediate upstream and downstream areas, could be regulating the phytoplankton standing crop. Consequently, it is postulated when the entrapment

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zone moved upstream in 1976 and 1977, the phytoplankton residence time in Suisun Bay (both the shallows and the channel) decreased resulting in the low phytoplankton standing crop in that area.

2. Upstream movement of the area of maximum flocculation-aggregation-settling. Suspended materials are characteristically low in San Francisco Bay and in the ocean. When Delta outflows were low during 1976 and 1977, the percentage of ocean water more than doubled in Suisun Bay over that of higher flow years (Figure 7). Furthermore, chlorophyll *a* levels during 1977 in Suisun Bay were similar to those observed in central San Pablo Bay during the higher flow years.

Increased flocculation, aggregation, and/or settling could occur in the area downstream of the entrapment zone - the area where the net vertical velocities are assumed to decrease.

It is uncertain why field phytoplankton standing crops were low in high salinity water (over 25 millimho/cm EC water) as growth rates were highest in similar salinities in our field and laboratory growth rate tests. One suggestion as to why the phytoplankton standing crop is characteristically low in high salinity water in the field is the phytoplankton are affected by the flocculation-aggregation-settling process and as a result are unable to maintain themselves in the euphotic zone downstream of the entrapment zone. Consequently, as the entrapment zone moved upstream throughout 1976-77, greater settling was assumed to have occurred in Suisun Bay.

3. Decreased phytoplankton residence time in the euphotic zone. Phytoplankton are concentrated where the entrapment zone is located. Their growth rate is directly proportional to the length of time they spend in the euphotic zone. When the entrapment zone is adjacent to the shallow bays the average water depth in the area occupied by the entrapment zone is much less than when the entrapment zone is located several miles upstream in the more confined channels. This assumes tidal exchange of the phytoplankton between the channel and the adjacent shallow bays. Therefore, when the entrapment zone was located upstream (1977), the entrapped phytoplankton spent less time on the average in the euphotic zone as compared to a downstream location. This hypothesis assumes top to bottom mixing.

4. Increased vertical mixing with reduced salinity stratification. During low Delta outflows (1977) the salinity stratification was less and the top to bottom mixing was assumed to be greater than during moderate to high summer outflows. The greater

salinity stratification during the higher summer outflows is postulated to maintain the algae near the surface and in the euphotic zone to a greater extent than during low outflows. Consequently, during low outflow the reduced stratification resulted in increased mixing which lowered the growth rate and standing crop.

5. Intrusion of marine benthic filter feeders. As previously discussed, it is uncertain at this time whether the upstream movement of marine filter feeding benthos influenced the phytoplankton crop in 1976 and 1977.

The following hypotheses may help account for the lower suspended materials concentrations typically found in the entrapment zone during periods of low flow (as compared to high outflow). However, if or how these hypotheses might have explained the low phytoplankton standing crop in Suisun Bay in 1976-77 is unknown.

1. Reduction of two-layered flow circulation. Theoretically, the intensity of two-layered flow circulation decreases as riverflow to the estuary decreases. The reduction in circulation could (a) increase the residence time of suspended materials in the entrapment zone, while at the same time, (b) reduce the quantity of suspended materials circulated through the zone. However, how these factors interact is unclear.

2. Reduced aggregation and settling. According to Krone (personal communications), high concentrations of suspended materials in the river water flowing into the estuary increases the chances of aggregation which in turn increases the settling rates of suspended materials. This is thought to increase the quantity of materials entrapped. Conversely, the quantity of suspended material entrapped decreases as the suspended materials concentration entering the estuary decreases. Generally, the concentration entering the estuary varies directly with riverflow.

DISSOLVED OXYGEN

Dissolved oxygen (DO) measurements were made in 1976 and 1977 during this study. Samples for the DO measurements were collected at both 1 meter from the surface and from the bottom (Figure 42). Measurements were conducted during daylight hours and during periods of low phytoplankton standing crop (20 ug/l chlorophyll a). The DO concentrations were near saturation. The bottom samples were typically a few tenths of a mg/l lower than the surface samples. The slight increase in DO concentration proceeding upstream was

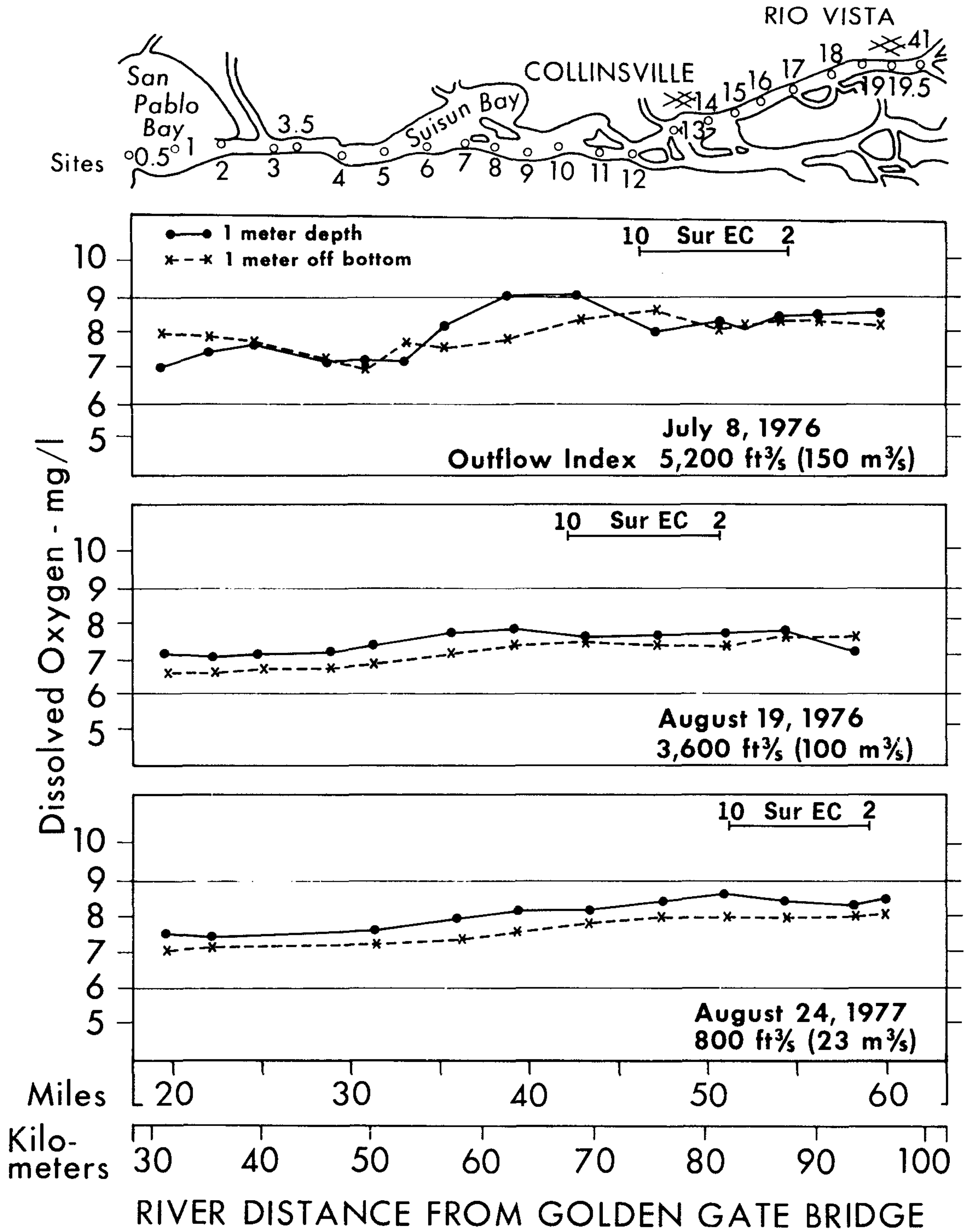

Figure 42. Near surface and bottom dissolved oxygen concentrations on high slack tides at low Delta outflows.

thought to result primarily from higher DO percent saturation levels for fresher water.

Routine daytime surface DO measurements in the Suisun Bay area were always near saturation (USBR, 1972 and Macy, 1976) even when chlorophyll a concentrations were relatively high (50-100 ug/l). Bottom measurements, however, were not made.

Presumably, tidal and wind mixing are adequate to maintain near-saturation levels at the current level of eutrophication in the western Delta-Suisun Bay area.

NEOMYSIS AND OTHER ZOOPLANKTON

The maximum abundance of *Neomysis mercedies* occurred in waters with specific conductivities of 2-10 millimho/cm (1-6 ^{o}/oo salinity) at the Delta outflows studied (Figure 43). This is the same salinity range where peak concentrations of suspended materials occurred. As with the other suspended materials, the *Neomysis mercedies* also shifted tidally (Figure 44).

Examination of the zooplankton data indicated two peaks of maximum copepod abundance throughout the study area. One peak was centered in the approximate location of maximum suspended solids concentration, while the other was downstream. Species identification by the DFG indicated *Eurytemora hirundoides* were predominant in the area of maximum suspended solids concentration while *Acartia clausi* was the predominant zooplankter downstream (Figure 45). *A. clausi* is known to be a more haline species than *E. hirundoides* (Kelly, 1966). As with the other suspended materials these zooplankton also shifted tidally (Figure 46).

In many estuaries zooplankton tend to concentrate at the upstream end of the freshwater-saltwater mixing zone, the entrapment area. The DFG has suggested during summer months the *Neomysis* and certain other zooplankton concentrations are directly related to the concentration of phytoplankton in the entrapment zone. It is interesting to note *Neomysis* (Figure 43) and zooplankton (Figure 45) concentrations were relatively high in March of 1974 - prior to the development of a phytoplankton bloom. Unfortunately, routine sampling did not extend downstream of Martinez to characterize the distribution of zooplankton during high Delta outflows.

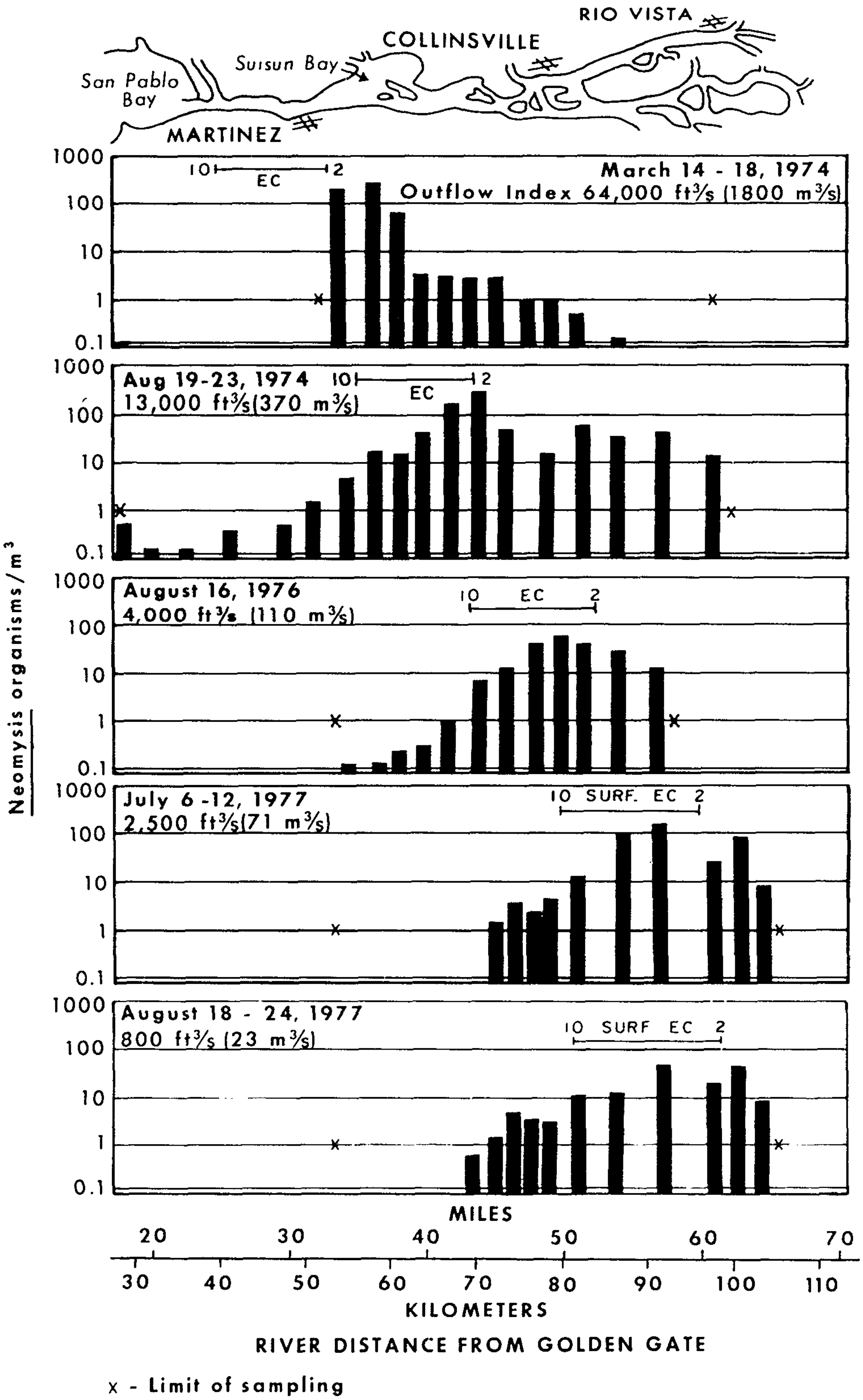

Figure 43. Distribution patterns of Neomysis mercedis relative to salinity on high slack tides at various Delta outflows.

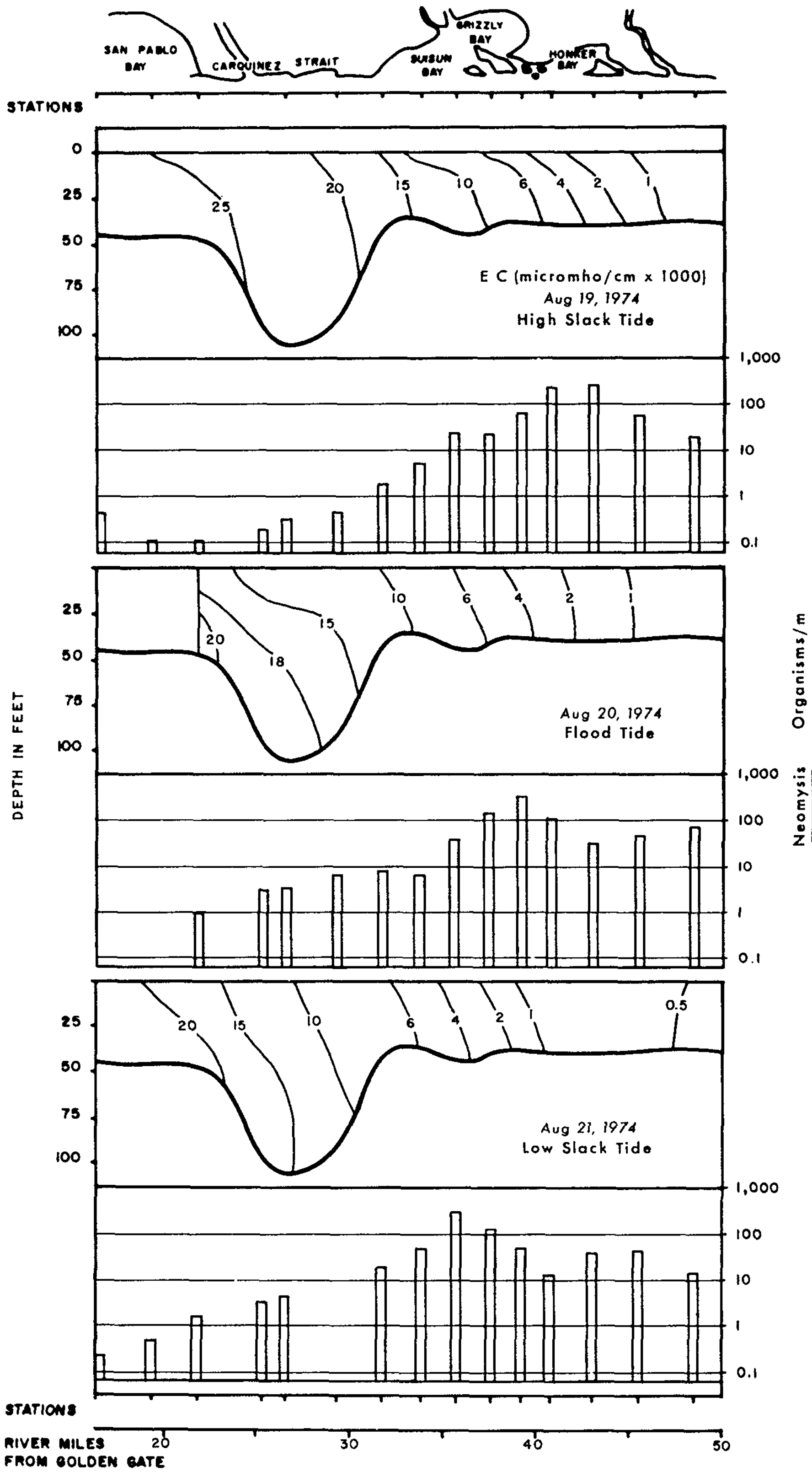

Figure 44. Distribution patterns of Neomysis mercedis relative to salinity on three consecutive days at different tidal phases in August 1974.

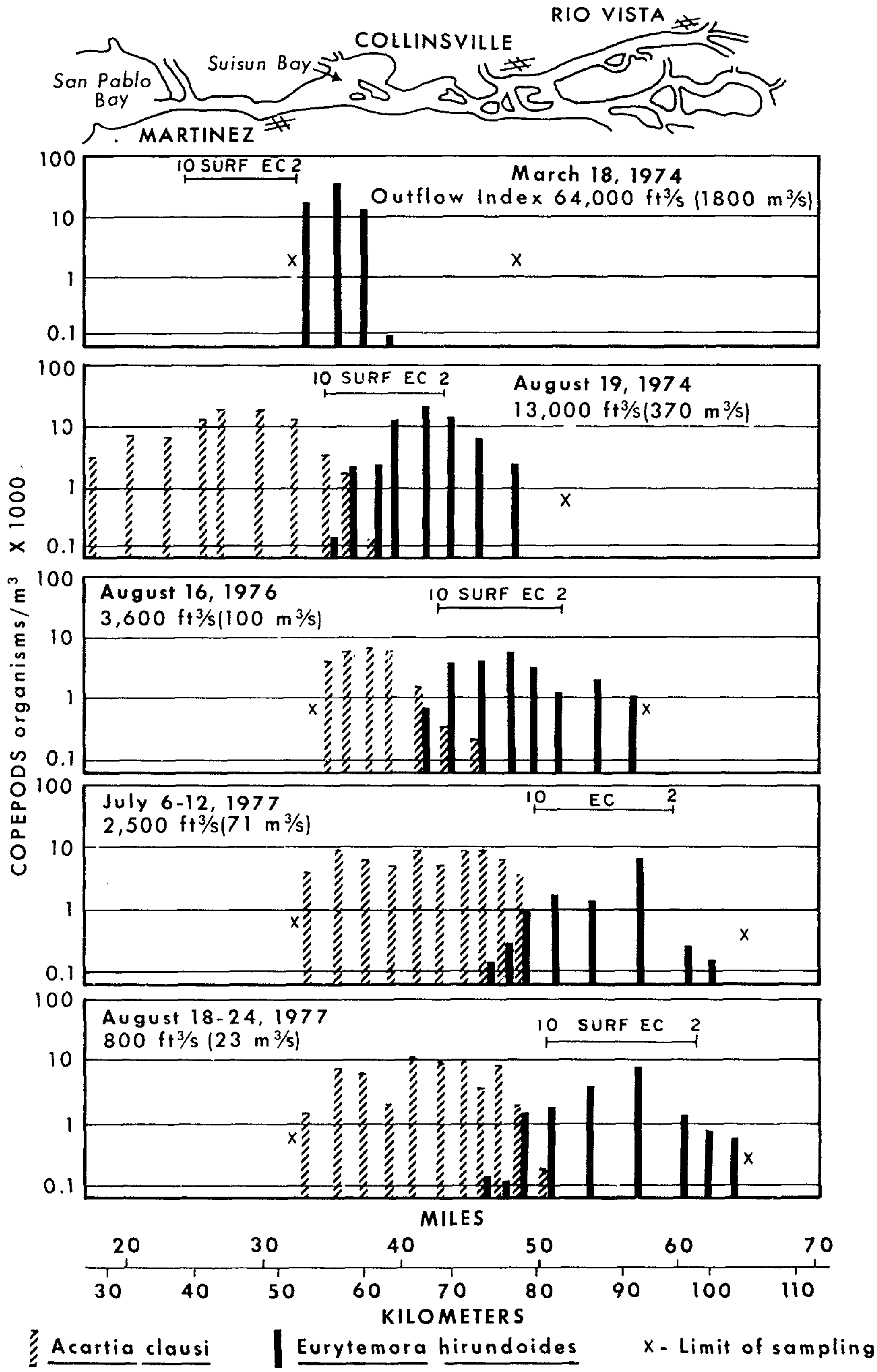

Figure 45. Distribution patterns of two dominant copepods (Acartia clausi and Eurytemora hirundoides) relative to salinity on high slack tides at various Delta outflows.

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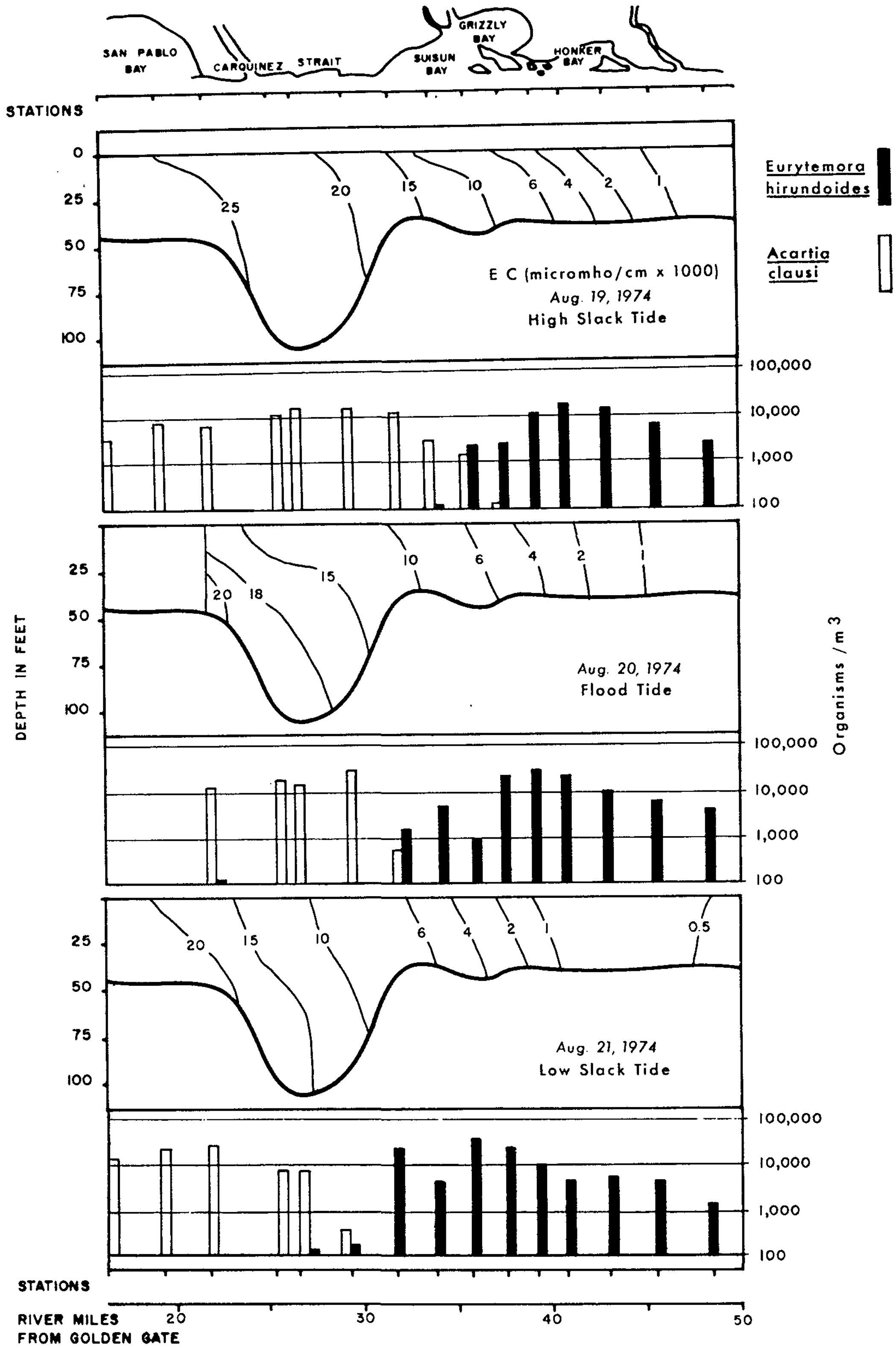

Figure 46. Distribution patterns of two dominant copepods (Acartia clausi and Eurytemora hirundoides) relative to salinity on three consecutive days at different tidal phases in August 1974.

Cronin and Mansueti (1971) state certain species of zooplankton have upward movement behavioral patterns during the night and downward during the day, which in a two-layer flow estuary translates into downstream transport at night and upstream transport during the day, resulting in roughly a circular motion which retains the species near its optimal salinity range. Heubach (1969) and Siegfried, et al. (1978) describes this vertical diurnal migration of Neomysis in the San Francisco Bay-Delta Estuary. Heubech (1969) also found their vertical distributions to be influenced by high tidal velocities.

The previous information leads us to believe the location of the maximum abundance of N. mercedies and certain copepods relative to salinity is influenced primarily by the interaction of the two-layered estuarine circulation on their instinctive vertical swimming behavior. Outflow and tidal action regulate their position in the estuary. Food supply could influence the maximum abundance in the entrapment zone.

The zooplankton data evaluated were limited to the same sampling periods and sites covered in this study. It was, therefore, impossible to ascertain whether the abundance of each zooplankton population studied decreased at the lower Delta outflows. According to the DFG (personal communications with Don Stevens) there was a definite decrease in total zooplankton abundance in the western Delta-Suisun Bay area during 1976 and 1977. This occurred because the center of the population shifted upstream into an area occupied by a smaller surface area and volume of water. Maximum concentrations observed in 1976 and 1977 were also lower than in 1973 and 1974.

STRIPED BASS

The distribution of juvenile striped bass (young-of-the-year) appears to be correlated to the distribution of other suspended constituents measured in this study. The distribution of juvenile striped bass is illustrated in Figure 47 for data collected in July 1973, 1974, 1976, and 1977. The peak concentrations occur in the 2-10 millimho/cm EC range. Similar distributions were noted for other periods of record (Turner and Chadwick, 1972).

It would seem that there are three possible explanations for the distribution patterns observed during these studies. First of all, they may swim to their optimal salinity range. Secondly, it is possible the bass swim to where the food supply peaks. Finally, the juvenile bass may still be essentially planktonic at this stage of their life cycle and are concentrated by two-layered flow

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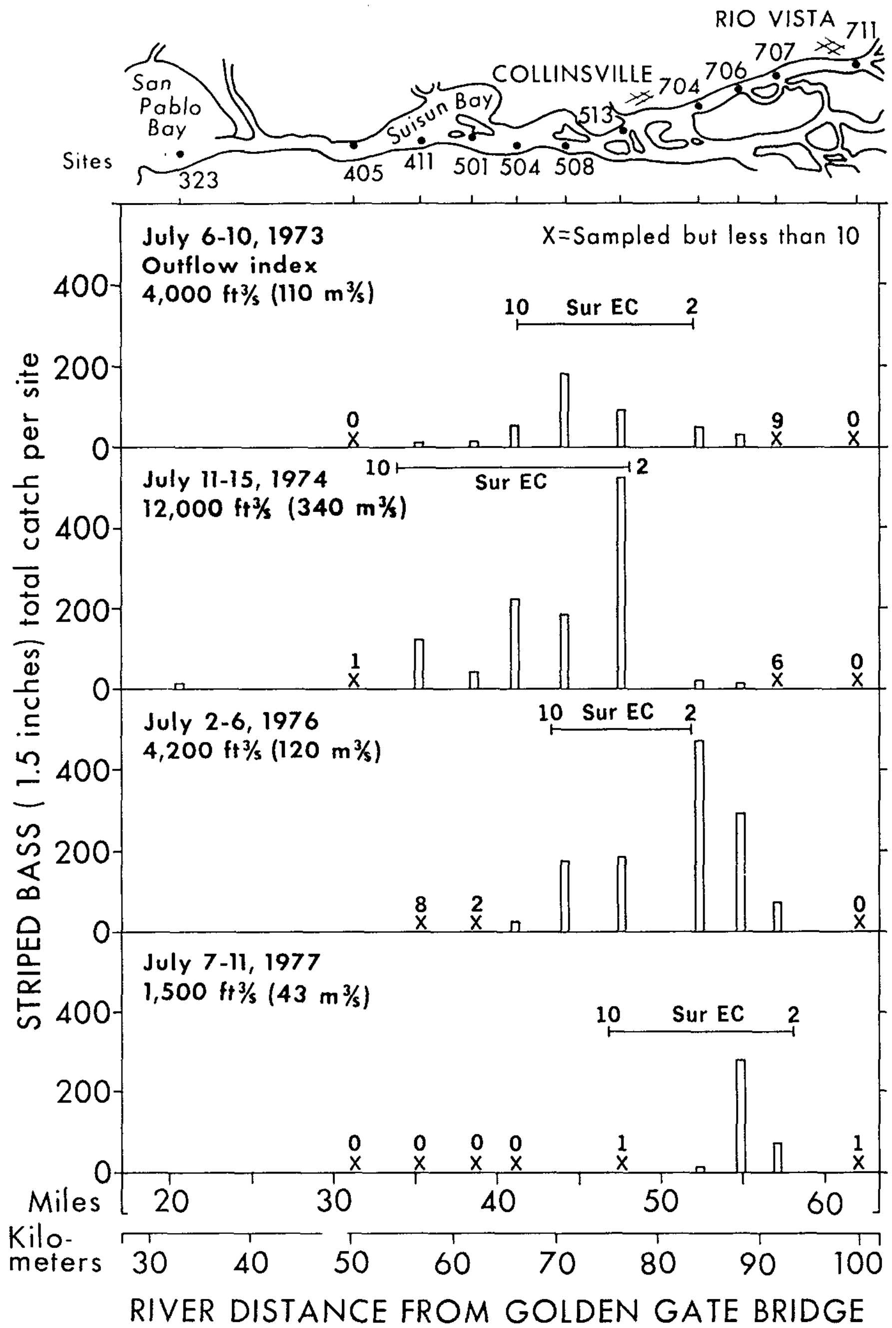

Figure 47. Distribution patterns of juvenile striped bass (young-of-the-year) relative to salinity on high slack tides during July of 1973, 1974, 1976, and 1977.

circulation. The latter explanation appears to be the most reasonable. Cronin and Mansueti, 1971, among others, state that the larval forms of many Atlantic Coast fish species that spawn both in freshwater and at the entrances to estuaries are carried to the plankton rich low salinity area (entrapment zone) where zooplankton are abundant.

Distribution of Constituents in the San Joaquin River

Sampling sites were established on the San Joaquin River between Pittsburg on New York Slough and the mouth of the Mokelumne River (Figure 2) during 1976 and 1977 low flow period. In general, the vertical salinity gradients, the distribution of suspended constituents, and the degree of salinity intrusion were similar to that observed in the Sacramento River. The peak concentrations of suspended materials occurred at approximately the same salinity range as in the Sacramento River, suggesting entrapment in both river systems during low Delta outflow. The entrapment zone was spread over a greater river distance in the San Joaquin River than in Sacramento River. This may be related to the net flow reversal in San Joaquin River system. Figure 48 illustrates the salinity gradients observed. The peak concentrations of turbidity and chlorophyll *a* relative to salinity (2-10 millimho/cm EC) are demonstrated in Figures 49 and 50.

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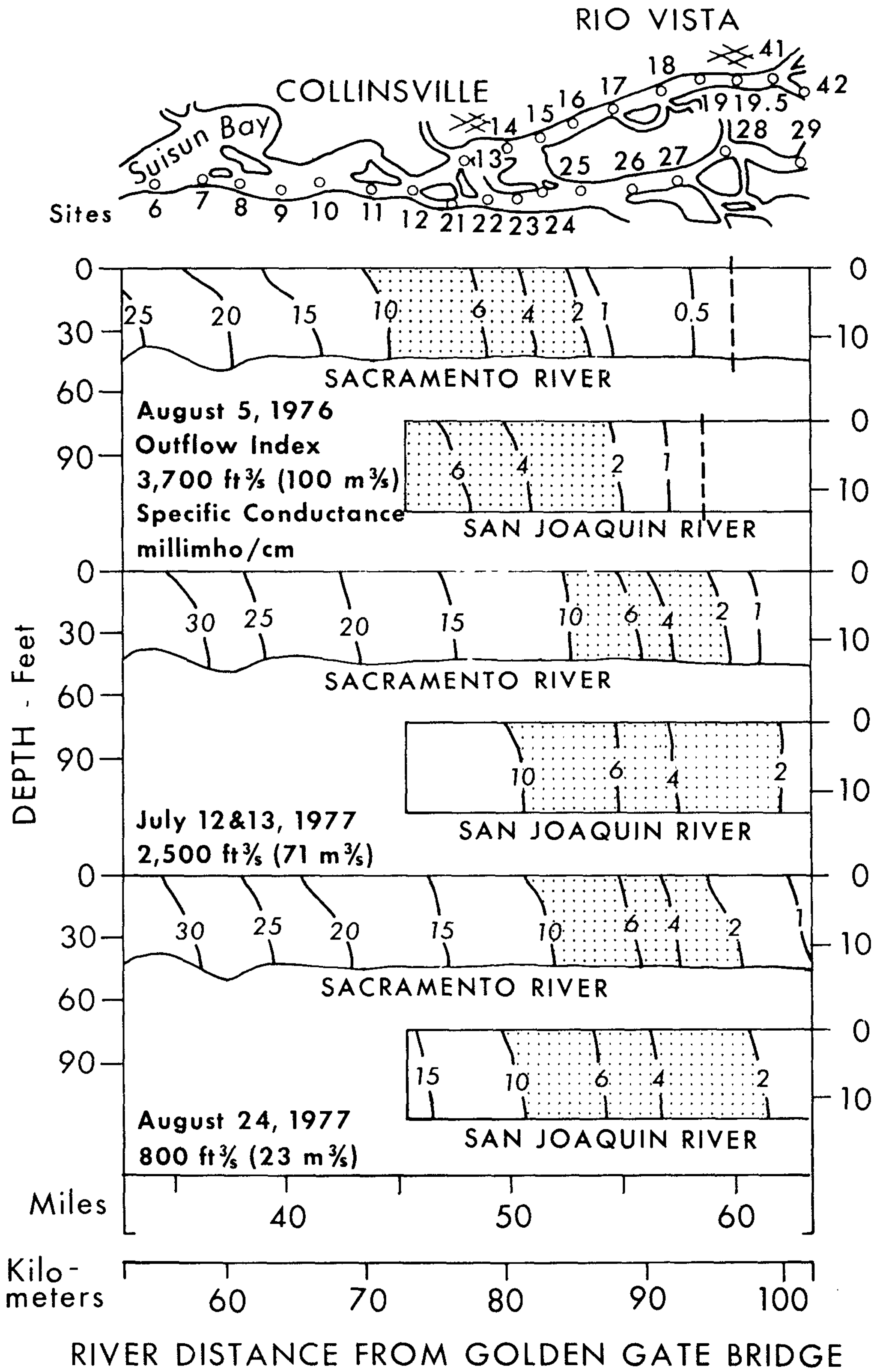

Figure 48. Isoconductivity contours in both the Sacramento and San Joaquin Rivers during low Delta outflow in 1976 and 1977.

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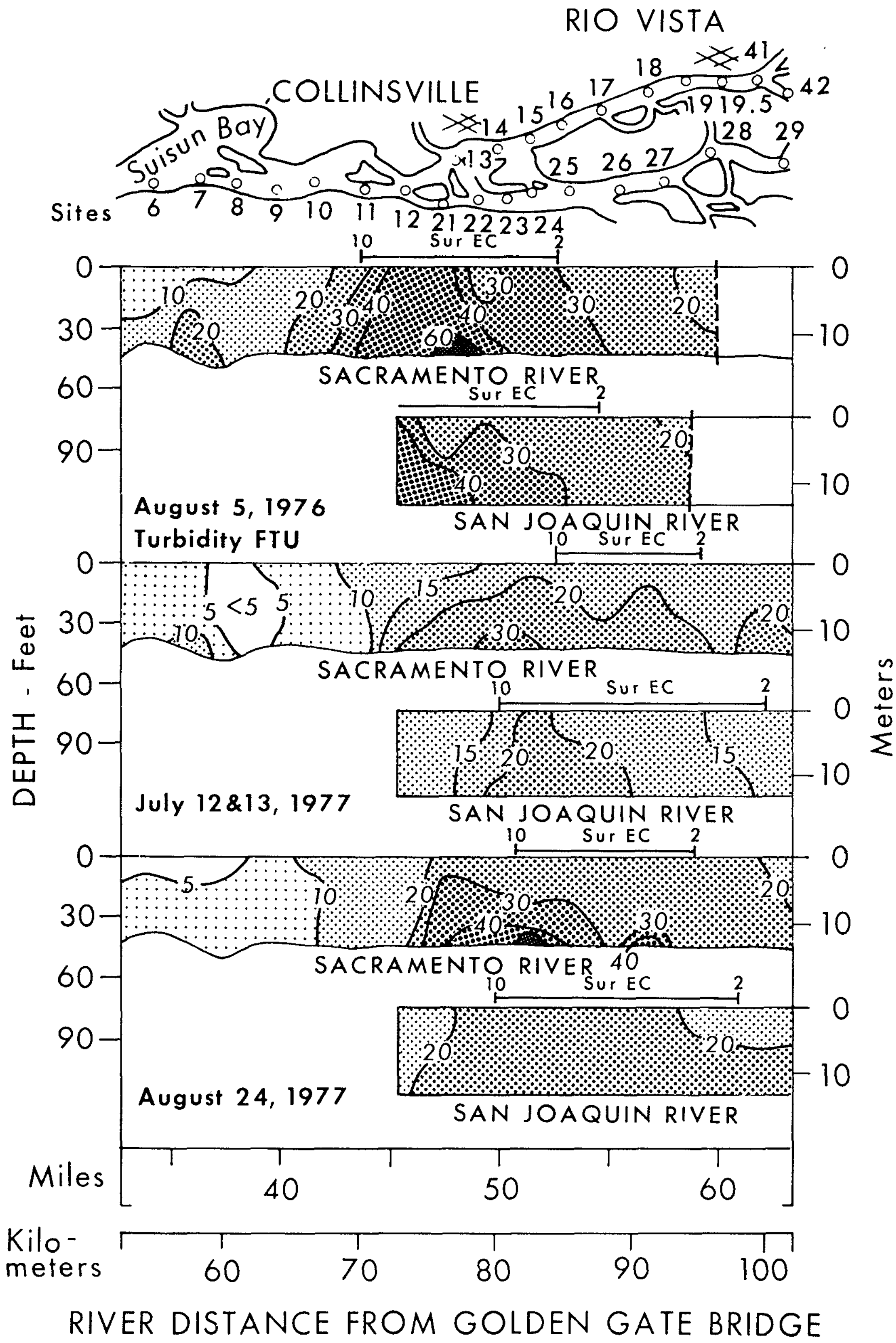

Figure 49. Distribution patterns of turbidity in both the Sacramento and San Joaquin Rivers relative to salinity on high slack tides during low Delta outflow in 1976 and 1977.

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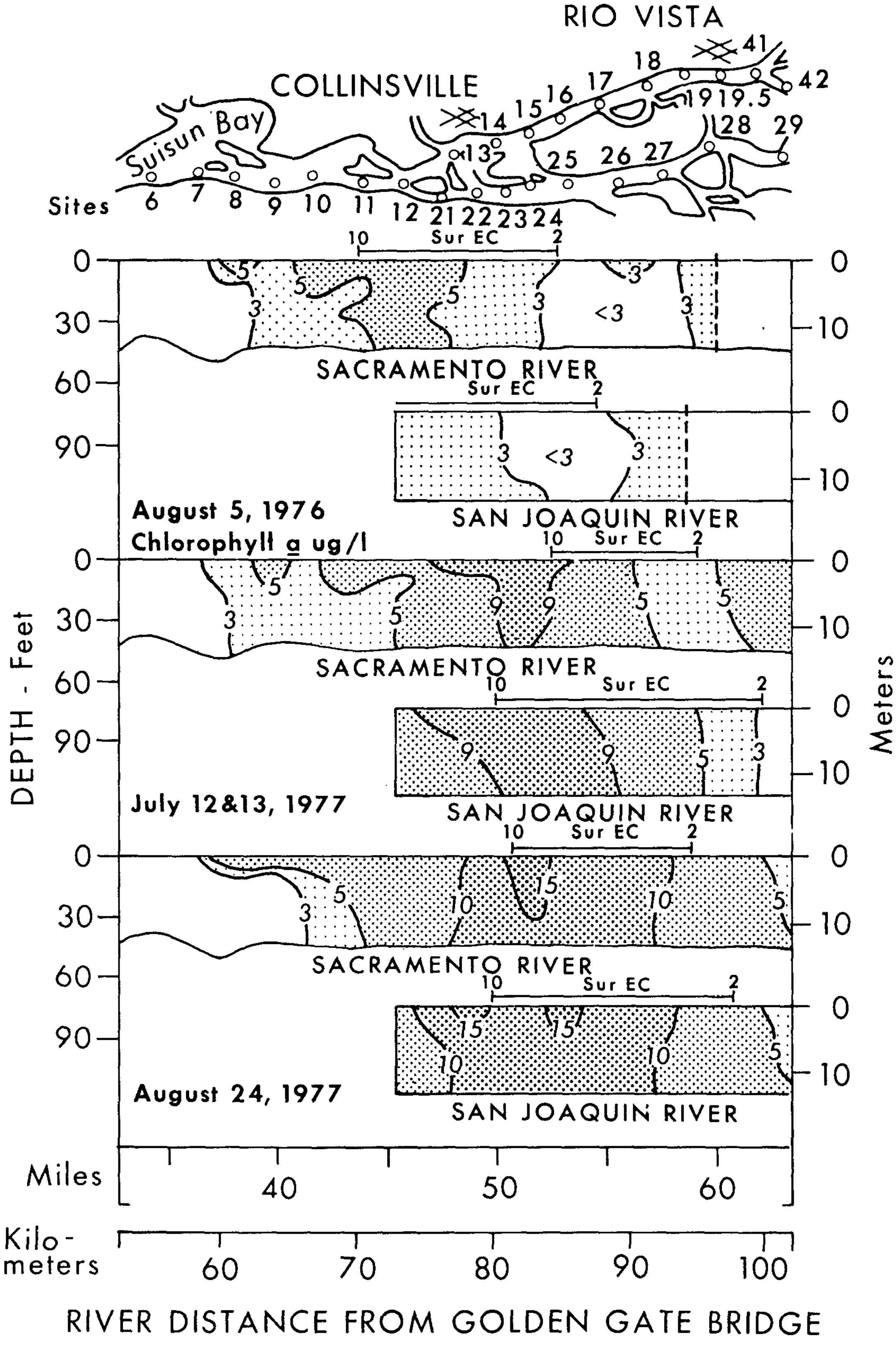

Figure 50. Distribution patterns of chlorophyll a in both the Sacramento and San Joaquin Rivers relative to salinity on high slack tides during low Delta outflow in 1976 and 1977.

ENVIRONMENTAL IMPLICATIONS

The overall goal of the USBR in the Interagency Ecological Study Program is to gain an understanding of how the Sacramento-San Joaquin Delta and upper San Francisco Bay-Delta Estuary function so that the total resources can be managed in the best possible manner. A primary objective of the USBR studies is to determine how changes in outflow and flow patterns, attributable to operations of water development projects, affect phytoplankton productivity and dissolved oxygen concentrations in the estuary. Specifically, this study has dealt with the influence of the entrapment zone on the distribution of suspended materials (including plankton) in the upper estuary.

The phytoplankton are important to the estuarine environment in that they are the primary producers that form the base of the food web. However, in many aquatic environments, high concentrations of phytoplankton have resulted in dissolved oxygen depletion to a point detrimental to higher aquatic organisms, created taste and odor problems in municipal water supplies, clogged filters in water treatment plants, and created esthetically undesirable conditions for recreationists. In the study area of the upper San Franisco Bay-Delta Estuary, however, phytoplankton problems are currently considered negligible, and the maximum desirable concentration of phytoplankton has yet to be determined.

Planned development of water in northern California, will result in an increased percentage of water exported from the Delta. The quantity of freshwater flowing through the estuary is important to phytoplankton growth in that it: (1) affects nutrient concentration; (2) determines sediment discharge and transport, which in turn influences the water transparency and light available for growth; (3) determines phytoplankton residence time; and (4) directly regulates salinity intrusion and the location of the entrapment zone. These and other environmental factors interact to determine the quantity and species of phytoplankton in the estuary.

Past data collected in the routine water quality monitoring program (1968-1975) during periods of average to high Delta outflows indicated the maximum phytoplankton standing crop in Suisun Bay increased with decreasing Delta outflows. High phytoplankton levels also occurred earlier in the year during the years with moderately low spring outflows and relative high water transparency.

The two lowest consecutive dry years on record were 1976 and 1977. Delta outflows in the summer and winter of 1977 were lower than those expected with future water development during normal or wet years. Although the 1976 and 1977 summer Suisun Bay water transparencies were nearly twice normal and nutrients were non-limiting, the phytoplankton concentrations were several times lower than observed in the previous 10 years. Also other suspended constituents measured in this study were at the lowest levels recorded for the Suisun Bay area in recent years.

The reduction in standing phytoplankton crop could not be attributed to the factors generally thought to influence phytoplankton growth. In examining 8 years of data, Ball (1977) observed the location of the entrapment zone, relative to the shallow areas of Suisun Bay, appears to be an important factor influencing phytoplankton concentrations in the upper estuary. Long-term phytoplankton data indicate the maximum concentration of phytoplankton occurs when the entrapment zone is located adjacent to Honker Bay. Upstream or downstream movement of the zone tends to correspond with a reduction in the phytoplankton concentration. Several ways have been suggested in which the upstream or downstream movement of the zone might influence the phytoplankton standing crop. It is difficult at this time, however, to make predictions as to what concentrations will occur in the future since the mechanisms controlling the phytoplankton standing crop are not fully understood nor can future waterway configurations or flow patterns be predicted with certainity.

Results of the data indicate Neomysis, certain other zooplankton, and juvenile striped bass (young-of-the-year) are concentrated in the entrapment zone, in part, by two-layered flow circulation. Undoubtedly, other estuarine organisms, not specifically measured in this study, are directly or indirectly influenced by the entrapment zone.

Data collected during 1976 and 1977 indicate when the entrapment zone was several miles upstream of the Suisun Bay area the total estuarine population of each of these organisms was reduced. It is uncertain how these reduced plankton populations will affect the adult striped bass and other fish populations.

Although not specifically studied, another problem of economic importance associated with the entrapment and mixing zones is shoaling. A prime example of the effects of increased shoaling occurred within the Savannah River Estuary (Meade, 1972) following development of upstream water diversion and dredging the channel for shipping. Not only did saltwater move farther up the estuary with the increased net landward bottom flows, but sediment that was formerly carried to the sea was then trapped in the estuary and sediment from outside the mouth was probably drawn into the estuary. Also, the floodflows that formerly flushed the estuary about every 3 years no longer occurred as frequently. Meade (1972) stated most of the sediment in the channel accumulated within a few kilometers of the nodal point where predominantly landward- and seaward-moving waters converge. This is approximately the location of the entrapment zone as identified in this report. Increased water diversion from the estuary and/or deepening of the ship channel in the San Francisco Bay-Delta Estuary will result in the upstream movement of the entrapment zone which, in turn, could result in an upstream shift in the location of greatest shoaling. Furthermore, according to Siegfried, et al. (1978), the benthic community associated with the entrapment zone will also move upstream. It is uncertain what affect this will have on the overall estuarine communities.

The reduction in Delta outflow will result in reduced turbidities in the entrapment zone and upper estuary. Since the desirable levels of turbidity are currently unknown it is ironic that Federal and State water quality criteria currently require discharges to the estuary to reduce the turbidity of their effluents.

In conclusion, data collected in the present study indicate that the entrapment zone is a significant environmental feature of the estuary. Studies are currently underway to determine more specifically how the phytoplankton and other water quality constituents are influenced by the entrapment zone.

ACKNOWLEDGMENTS

The USBR wishes to express this appreciation for review of the draft report by the staff members of the Interagency Ecological Study Program and to Randall Brown, DWR. We wish to thank the DFG and DWR for use of their staffs, facilities, and boats and other staff members in the USBR for their work on this study.

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